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RESEARCH MEMORANDUM

IGNITION DELAY EXPERIMENTS WITH SMALL-SCALE ROCKET
ENGINE AT SIMULATED ALTITUDE CONDITIONS USING
VARIOUS FUELS WITH NITRIC ACID OXIDANTS

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NATIONAL ADVISORY COMMITTEE
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RESEARCH MEMORANDUM

IGNITION DELAY EXPERIMENTS WITH SMALL-SCALE ROCKET ENGINE

AT SIMULATED ALTITUDE CONDITIONS USING VARIOUS FUELS

WITH NITRIC ACID OXIDANTS

By Dezso J. Ladanyi

SUMMARY

Ignition delay determinations of several fuels with nitric acid oxidants were made at simulated altitude conditions utilizing a small-scale rocket engine of approximately 50 pounds thrust.

With aniline and red fuming nitric acid at room temperatures, ignition delays obtained at initial ambient pressures corresponding to altitudes to 88,000 feet were not significantly different from values obtained at sea-level pressure.

At or below -10° F, explosions or long ignition delays were experienced with hydrazine hydrate and white fuming nitric acid.

Several fuels and various nitric acid oxidants were tested at about -40° F and sea-level pressure. Anhydrous nitric acid always yielded a shorter delay than white fuming nitric acid when tested with the same fuel. The combination that ignited most rapidly was a diallylaniline - triethylamine mixture and anhydrous nitric acid, which yielded an average ignition delay of about 14 milliseconds.

With a diallylaniline - triethylamine mixture and white fuming nitric acid, ignitions with average delays ranging from 9 milliseconds at 110° F to 22 milliseconds at -50° F were obtained regardless of the initial ambient pressure that ranged from sea-level pressure to a pressure altitude of 88,000 feet. An explosion occurred after ignition in several cases.

With a diallylaniline - triethylamine mixture and a red fuming nitric acid analyzing 3.5 percent water and 16 percent NO_2 by weight, ignitions with no ensuing explosions were obtained with average delays ranging from 13 milliseconds at 110° F to 55 milliseconds at -95° F regardless of the initial ambient pressure that ranged from sea-level pressure to a pressure altitude of 94,000 feet.

From all the runs, it was determined that ignition delay was unaffected by wide variations in time between propellant entries into the combustion chamber.

It was also determined that, with aniline and red fuming nitric acids with essentially equal water contents, a variation in the NO₂ content of the acid from 29 to 35 percent had no significant effect on ignition delay. With other fuels and nitric acids, a decrease in the NO₂ content from 2.5 to 0.5 percent accompanied by a simultaneous increase in the water content from 0.2 to 1.8 percent increased the ignition delay.

INTRODUCTION

The problem of starting rocket engines at conditions of various altitudes up to 100,000 feet has been receiving considerable attention recently because of its importance in the development of air-to-air missiles, air-to-surface missiles, and rocket-propelled airplanes that require starting at low pressures and temperatures. Many self-igniting liquid rocket propellant combinations that perform satisfactorily at temperate sea level will not ignite at the low temperatures of higher altitudes or of arctic regions primarily because of decreased initial chemical reaction rates. Pre-impingement vaporization of a propellant at low pressures also may cause ignition difficulties.

From results obtained with a capillary twin-jet apparatus, it was concluded that ignition delay in an actual rocket will increase with a decrease in initial ambient pressure and that sufficient amounts of propellants may accumulate in the combustion chamber prior to ignition to cause an explosion (reference 1). Similar conclusions were reached as a result of visual injection experiments at low pressures (reference 2). Studies of ignition at low temperatures by several investigators have been corroborative on the general observation of increased ignition delay with decrease in temperature (for example, references 3 to 6). Such studies have been considerably more extensive than contemporary research at low pressures.

As part of a general investigation of the ignition characteristics of self-igniting rocket propellant combinations conducted at the NACA Lewis laboratory (references 6 to 8), determinations of ignition delays of several fuels with nitric acid oxidants were made at simulated altitude conditions utilizing a small-scale rocket engine of approximately 50 pounds thrust. This phase of the research, conducted from April 1950 to June 1951, was first directed toward determining the effects of various subatmospheric pressures on the ignition delay of the aniline - red fuming nitric acid combination while, at the same time, determining the reliability of the apparatus as an ignition delay measuring device. Another portion of the ignition work reported herein

was the establishment of a temperature - ignition delay relation for the hydrazine hydrate - white fuming nitric acid combination currently proposed for the starting system of a rocket engine now in the development stage (reference 9). Since minimum equipment design temperature for aircraft at 45,000 feet altitude with indicated air speed of 150 miles per hour is approximately -95° F (reference 10), and since a contemplated specification for this engine as well as others under development may be repeated successful starts at these conditions, other fuels and modified nitric acids were investigated in attempts to meet these requirements. The results of these experiments and a few related tests are described herein.

APPARATUS

General Description

The apparatus consisted of a small transparent-chamber rocket engine of approximately 50 pounds thrust, propellant tanks, a gas pressure-supply reservoir, a photographic system for ignition-delay measurement, means for obtaining and controlling propellant temperature and initial ambient pressure, and instrumentation for indicating and recording combustion-chamber pressure and other operating variables. Figure 1 is a diagrammatic sketch of the apparatus. A photograph of the over-all equipment is shown in figure 2.

Pressurized helium contained in a 2100-cubic-inch reservoir served to force the propellants from their tanks through injector nozzles and into the combustion chamber when a quick-opening solenoid valve was opened. Sealing disks at each end of the propellant tanks were burst in the process. Photographs were taken of the two propellant streams entering the combustion chamber, impinging, diffusing, and then igniting. Measurements of the ignition delay period were made from the photographic data.

Rocket Engine Design

The rocket engine assembly consisted of an injector head, injector nozzles, a transparent cylindrical combustion chamber, a plate with a convergent exhaust nozzle, and propellant tanks. Figure 3 is an assembly photograph. Figure 4 shows an exploded view.

The injector head assembly is shown in figure 5. The head was drilled and tapped to receive two propellant injector fittings at an included angle of 90°. A combustion-chamber pressure tap was located in the center of the head. The 0.041-inch-nozzle-diameter fuel injector and the 0.064-inch-nozzle-diameter oxidant injector were located so that

the ejected streams would travel 0.68 inch before impinging. Each injector had a conical entrance leading to a straight 0.38-inch-long orifice tube with a chamfered exit. Polymeric methylmethacrylate tubing, 4 inches long and 2 inches inside diameter, was used for the combustion chamber.

The propellant tank assembly included a burst diaphragm at each end. Hardened stainless steel cutting dies were used in conjunction with unscored 0.003-inch-thick aluminum (2S-0) diaphragms. The dies were designed to cut the disks without fragmentation and with an applied pressure of less than 100 pounds per square inch. An unused disk, a cutting die, and a burst disk are shown in figure 6. The fuel and oxidant tanks had capacities of approximately 100 and 200 cubic centimeters, respectively. The components of this assembly are shown in figure 4.

The rocket engine was designed to operate for three seconds at 50 pounds thrust with a typical propellant combination (aniline and red fuming nitric acid) at sea-level temperatures and pressure. Design parameters included a specific impulse of 180 pound-seconds per pound, a total oxidant-to-fuel weight ratio of 3, a ratio of chamber volume to throat area (I^*) of 98 inches, and a difference of 100 pounds per square inch between the injection and combustion-chamber pressures. The calculated total weight flow was 0.28 pound per second.

With coefficients of discharge calculated for the injectors from actual flow data obtained with water at 77° F, an oxidant-to-fuel weight ratio of 3.1 at 77° F was obtained for the preignition period of aniline and red fuming nitric acid containing 29 percent (by weight) of nitrogen dioxide.

Equipment for Simulating Altitude

The rocket engine was mounted vertically on a 44-inch-long, 12-inch-diameter standpipe connected by a 6-inch-diameter seamless steel pipe to a 1500-cubic-foot cylindrical tank that could be evacuated to an NACA standard pressure altitude of about 100,000 feet. This altitude tank and accessories have been described previously (reference 8).

Beginning with run 57, the propellant tanks were immersed in a constant-temperature alcohol bath contained in a tank welded directly to the injector head (figs. 3 and 4). The temperature of the bath was accurately and automatically controlled by means of a dual heat-exchanger and blending system. Any desired propellant temperature in the range from -95° to 110° F covered in this investigation was obtained within twenty minutes after starting the circulation pump in the system. A mixture of dry ice and denatured alcohol and electrically heated water were used in the cold and hot heat exchangers, respectively.

Instrumentation

The following measurements were made:

- (1) Combustion-chamber pressure
- (2) Propellant injection pressure
- (3) Altitude-tank pressure
- (4) Temperature of fuel, oxidant, injector head, constant-temperature bath, nozzle plate, and ambient air
- (5) Time between the entries of the two jets into the combustion chamber
- (6) Ignition delay period
- (7) Time between ignition and explosion if the latter occurred

The combustion-chamber pressure was measured and recorded by a calibrated Bourdon-tube-type strip chart instrument having an accuracy of ± 5 pounds per square inch. The propellant injection pressure was indicated on a calibrated Bourdon-tube-type gage and recorded by the operator just before firing. This gage had an accuracy of 2 percent of full scale (600 lb/sq in.). Beginning with run 113, photographs were taken of this gage about 3 seconds before the solenoid valve opened. The altitude-tank pressure was measured by a diaphragm-type absolute pressure gage. Copper-constantan thermocouples were used for temperature measurements. Propellant temperatures were measured near the centers of the tanks. Thermocouples were imbedded $1/4$ inch into the injector head and nozzle plate. The air temperature was measured near the engine assembly. The locations of the thermocouples are shown in figures 2 and 3. The temperatures were measured and recorded by a calibrated self-balancing potentiometer with an accuracy of $\pm 1^\circ$ F.

The action within the combustion chamber was photographed in silhouette by a 16-millimeter high-speed camera with a built-in timing light and with a maximum speed of 5000 frames per second. The required light was produced by a bank of flood lamps focused on a white background with the reflected light passing through the combustion chamber and into the camera lens. The photographic installation can be seen in figure 2.

Propellants

Eight fuels, pure or blended, and ten nitric acid oxidants were used in 18 propellant combinations in this investigation. Analyses of

the nitric acid oxidants are given in table I. Physical properties of the fuels and important oxidants are listed in tables II and III, respectively. The oxidants are coded in the tables for convenient reference. The first number after the acid indicates its approximate water content by weight. The second number, if used, is the NO_2 content. Additives with corresponding weight percent are enclosed in brackets.

The following fuels were used:

- (1) chemically pure aniline
- (2) aqueous solutions of hydrazine approximating the composition of hydrazine hydrate (two solutions)
- (3) furfuryl alcohol
- (4) commercial gum turpentine
- (5) furfuryl mercaptan
- (6) a mixture of 50 percent mixed xylidines and 50 percent triethylamine (by volume at room temperature)
- (7) a mixture of 57 percent diallylaniline and 43 percent triethylamine (by weight)

The hydrazine hydrate solutions were prepared by adding a calculated amount of distilled water to hydrazine solutions analyzing approximately 92 percent hydrazine (by weight). The mixed xylidines used in the fuel mixture preparation was obtained from the Cactus Ordnance Works. The diallylaniline was furnished by the California Research Corporation through the Bureau of Aeronautics, Department of the Navy.

The nitric acid oxidants included red fuming nitric acids (RFNA), white fuming nitric acids (WFNA), white fuming nitric acid with additives, and anhydrous nitric acid. Several commercial lots of chemically pure red fuming nitric acid presumably saturated with NO_2 were used.

Analyses revealed that the NO_2 content actually varied from 20- to 35- percent by weight (RFNA-0-20, RFNA-0-22, RFNA-0-25, RFNA-4-29, and RFNA-5-35). A low-freezing-point acid (RFNA-4-16) was prepared by blending RFNA-0-20, RFNA-0-25, anhydrous nitric acid, and water. The component acids were mixed and then cooled below -40°F . Water was added to the acid slurry. The mixture was agitated in an enclosed container and allowed to warm up slowly to room temperature to yield a clear homogeneous solution. Two of the white fuming acids met the USAF Specification No. 14104 (WFNA-2 [lot a] and WFNA-2 [lot b]). WFNA-7 was more dilute. Additives were used with WFNA-2 [lot a] in an effort to depress its freezing point and shorten its ignition delay with fuels. Potassium nitrate was employed in one case

(WFNA-8 [6-KNO₃]) and perchloric acid in another (WFNA-11 [4-HClO₄]). Nitric acid designated as anhydrous in this investigation actually contained a small amount of water (about 0.2 percent by weight).

PROCEDURE

Test Preparations

The propellant tanks were loaded and then completely sealed by inserting bursting diaphragms and cutting dies between the tank bodies and end fittings. Equal ullages, obtained in the propellant tanks when 100 cubic centimeters of fuel and 195 cubic centimeters of oxidant were used, aided attempts to inject the propellants into the combustion chamber simultaneously.

The rocket engine assembly was bolted together to a measured torque of about 400 pound-inches. Spacers around the bolts prevented heat distortion of the chamber during a run and consequent leaking. The propellant tanks were then screwed into the injector head and the helium inlet lines were connected to the tanks.

For all runs, the propellant injection pressure was 450 pounds per square inch gage. Although injection pressures higher than this amount were not used in this investigation, other runs at lower pressures indicated that 450 pounds per square inch gage is near the maximum pressure beyond which there would be little additional effect on ignition delay. Two methods were employed in this investigation to supply the desired propellant injection pressure. For runs 1-120, the supply reservoir was filled to the proper pressure with helium from a commercial bottle. The injection pressure remained essentially constant during a run, decreasing less than 5 pounds per square inch for the entire run and about 1 pound per square inch during the ignition delay period. For the remainder of the runs, the commercial helium bottle was permanently connected to the reservoir and a pressure loader kept the injection pressure constant before and during a run.

Runs 1 to 56 were conducted at room temperature without any attempts being made to control the propellant temperature. The remaining runs were made with close regulation of the fuel and oxidant temperatures by means of a heat-exchanger system described previously. Beginning with run 128 and only for runs below 32° F, a small flow of helium was passed continuously through the combustion-chamber pressure line during the cooling period to prevent clogging by ice formation. The flow was stopped just before each run.

For runs made at pressures different from sea-level, the large altitude tank was evacuated prior to firing by a rotating-oil-seal-type vacuum pump, which reduced the pressure correspondingly in the

exhaust standpipe as well as in the rocket combustion chamber. The pressure in the standpipe did not change significantly during the ignition delay period. The initial pressures are given in millimeters of mercury as well as in terms of NACA standard pressure altitude (references 11 and 12).

Engine Operation

After the preliminary steps were completed, the actual operation of the apparatus was almost completely automatic. The entire sequence of events during a normal run was controlled by a preset electrical program timer.

When the three-way helium supply valve was opened, the pressurized inert gas ruptured the propellant tank diaphragms and forced the propellants into the combustion chamber. About 3 seconds later, the interior of the vertical exhaust standpipe was sprayed with water, quenching the products of combustion and preventing, by dilution, any further chemical reaction. Upon complete ejection of the fuel and oxidant from the propellant tanks, the engine assembly was automatically purged by the ensuing helium. De-energization of the solenoid controlling the helium valve cut off the gas flow and vented the propellant tanks to the atmosphere. In cases of emergency, both the water spray system and the helium supply valve could be operated independent of the program timer.

Interpretation of the High-Speed Photographic Data

For the runs in this investigation, the camera speed ranged from 3000 to 4500 frames per second, determined from argon-light timing marks on one edge of the film.

Most of the runs were photographically similar. In all cases, the exact frame of the entry of each jet into the combustion chamber was clearly discernible. At the moment that the two jets met, a copious amount of dark fumes (probably oxides of nitrogen) began to be evolved. These fumes quickly filled the chamber and usually made it completely opaque. The ignition point was determined by the frame in which a sudden evolution of light occurred that encompassed about $1/20$ to $1/4$ of the projected chamber area. In most runs, the bright area increased rapidly and the normal combustion pattern was established in 3 to 6 frames, or about one millisecond. With certain propellant combinations at -40°F (for example, runs 79 and 80), the ignition point was difficult to determine because the initially lighted area was small and faint and the full combustion picture was not obtained for more than 40 milliseconds.

[REDACTED]

2349 The photographic record of a typical run (run 11) is shown in figure 7. The oxidant jet entered the combustion chamber in frame 7; 13.7 milliseconds later, the fuel jet entered and intersected the oxidant stream (frame 65). Fumes were evolved and filled the combustion chamber. Ignition occurred in frame 207, 33.5 milliseconds after the meeting of the propellants. (This period is called the ignition delay.) The pressure rise accompanying ignition purged the combustion chamber of dark fumes in 1 millisecond and normal burning was established. Photographs made in color (runs 71 and 76) show that the light recorded at the ignition point is actually a high-color-temperature light emitted by the combustion reaction rather than conceivably the low-color-temperature reflected flood light penetrating the chamber being cleared of fumes by a sudden nonluminous pressure rise.

Some runs were designated as "hard starts" or "explosions". A hard start was an excessive pressure rise of short duration, occurring with a loud report immediately after ignition and without destroying the combustion chamber or causing other damage. Visually, it was distinguishable by the development of extremely bright light that was photographically recorded beyond the limits of the projected combustion-chamber area and that persisted for about 6 milliseconds before the normal combustion picture was established. In some cases, escaping fumes indicated a momentary separation between the combustion chamber and the injector head or nozzle plate.

All explosions that were encountered occurred ordinarily less than 7 milliseconds after ignition; the usual destruction of the combustion chamber marked the explosion point. In run 55, an explosion flexed the combustion chamber without destroying it but damaged other external equipment. This may have been caused by pressure waves induced by rapid flexures of the combustion-chamber wall. Since the development of a hard start and explosion are visually similar, an explosion might be considered a hard start severe enough to destroy the combustion chamber or cause other damage.

An example of a run resulting in an explosion is shown in figure 8 (run 77). The fuel entered the chamber in frame 6. The oxidant followed 5 milliseconds later (frame 24). After a delay of 43 milliseconds, ignition occurred (frame 181). An explosion began to develop terminating in the destruction of the combustion chamber 3.8 milliseconds after ignition (frame 195).

RESULTS AND DISCUSSION

Aniline and Red Fuming Nitric Acid

The initial runs in this investigation were made to determine the effects of low ambient pressures on the ignition delay of aniline and

red fuming nitric acid containing 29 to 35 percent NO_2 (by weight); 21 runs were conducted at temperatures from 88°F to 30°F (near the freezing point of aniline) and from sea-level pressure to a pressure altitude of 88,300 feet. Of these, five terminated in explosions. The results of these experiments are shown in table IV.

A plot of the data showing ignition delay as a function of temperature is shown in figure 9. The dotted lines envelop all runs that did not result in an explosion or burn-out; the solid line indicates an average for these runs. The deviation from the average was about 2 milliseconds at any particular temperature. For the normal runs, the variation of ignition delay with temperature in the range covered in these experiments varied from an average of about 18 milliseconds at 84°F to about 36 milliseconds at 30°F ; variations in initial ambient pressure from sea-level pressure to a pressure altitude of 88,300 feet in the temperature range of 60 to 82°F had no significant effect on ignition delay. Of 10 runs at sea-level pressure, three resulted in explosions; of 11 runs at pressure altitudes from 40,700 to 88,300 feet, two were terminated by explosions. These results indicate that low ambient pressure was not the determining factor in causing the engine failures. In studies of the behavior of liquid streams injected into a large low-pressure chamber (reference 2), a marked fanning or disintegration of the streams occurred at pressures below the vapor pressure of the liquid. It was concluded therein that this effect may result in violent engine failure. A possible explanation of the differences between the conclusions of reference 2 and the results reported herein is as follows:

The combustion chamber of an actual rocket engine is almost a totally enclosed cylinder. The outward diffusion of any accumulated vapors through the nozzle is restricted; therefore, although the initial portion of the entering oxidant vaporizes quickly at low pressures, ensuing portions cease to boil because of the rapid attainment of a total ambient pressure greater than the vapor pressure of the acid. Actually, a small amount of the entering acid continues to evaporate in order to replace the amount lost by diffusion through the nozzle. In accord with this explanation, the results show no meaningful change in ignition delay between runs conducted at sea-level pressure and runs initiated below the vapor pressure of the oxidant. Further accord is given by results that indicate that the reduction of ambient pressures that are already below the vapor pressures of the propellants do not influence ignition delay any more significantly. This can be seen by comparing runs 45 and 54 (table IV) conducted at about 80°F and at pressure altitudes of 50,700 feet and 81,800 feet, respectively. Both runs were initiated with the ambient pressure below the vapor pressure of the oxidant and yielded ignition delay values differing by only one millisecond.

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In references 1 and 2, liquids were injected into a large vacuum chamber that cannot be compared to a relatively small rocket chamber. The photographs of reference 2 showing stream disintegration were taken almost immediately after the injection was started. This disintegration, measured by the spray-cone angle, decreased with time as the chamber pressure increased. If a smaller chamber had been used and injection photographs had been shown following the initial one, rapid spray cessation and subsequent normal stream flow might have been perceived. This was shown by the high-speed photographs of runs 42, 43, 45, 52, and 53. For example, in run 45 (at 80° F and a pressure altitude of 50,700 feet), the oxidant preceded the fuel into the combustion chamber by 26.3 milliseconds. The acid entered the chamber as a very diffuse spray but a normal solid stream was established soon thereafter. This transformation is shown by the photographs in figure 10. The oxidant entered the chamber in frame 11 and a clearly defined jet had formed by the time the fuel entered (frame 121). Ignition occurred in frame 204 after a normal ignition delay of 19.7 milliseconds. The rapidity of the transformation would probably decrease with an increase in combustion chamber size, with an increase in throat area, or with a decrease in oxidant flow. With a large enough chamber, a large enough throat area, or a small enough acid flow, the prediction of engine failure at low initial ambient pressure (reference 2) might be quite valid.

With nitric acid oxidants, another factor that contributes to the rapid establishment of a solid acid stream is the pressure rise produced by the oxides of nitrogen and by other gases that are evolved as soon as the fuel and oxidant meet in the combustion chamber. This was suggested by low-pressure runs in which diffuse acid entered the combustion chamber and intersected an established preceding solid fuel stream and in which normal ignition delays still were obtained. Chemical reaction and the ignition delay period started as soon as the oxidant met the fuel. An example (run 44) is shown in figure 11. This run at 69° F and a pressure altitude of 74,700 feet resulted in a delay of 23.5 milliseconds. The fuel entered the chamber in frame 16. The acid entered 3.0 milliseconds later (frame 28). The ignition point is seen in frame 122.

The discussion thus far has been restricted to normal runs, that is, runs not resulting in explosions or burn-outs. With one exception (run 49), all the abnormal runs yielded values for ignition delay that were 4 to 13 milliseconds longer than the average normal values at the various temperatures of the runs. The explosions of runs 46, 47, 49, and 50, and the burn-out of run 56 occurred 0.6 to 7.9 milliseconds after ignition. The causes of these explosions are unknown. It was observed that in the abnormal runs the aniline preceded the acid into the combustion chamber without exception. Neither the length of time of this precession, propellant temperature, initial ambient pressure, nor ignition delay period could be correlated with the production of an explosion.

Hydrazine Hydrate and White Fuming Nitric Acid

A series of runs was made at sea-level pressure with hydrazine hydrate and white fuming nitric acid (USAF Specification No. 14104) to determine its ignition delay and reliability of ignition at temperatures from 110° F to the lowest limit of serviceability. These propellants were tentatively selected as a starting combination for an engine required to ignite as low as -40° F (reference 13). In the development of the engine, successful starts were made in a 50-pound thrust engine down to -40° F (reference 9). Another laboratory found that it was not possible to secure reliable ignition data at low temperatures (-36° F to -58° F) with a similar combination (WFNA and eutectic hydrazine) used in a small-scale engine of 50 pound thrust (reference 3); however, more reproducible ignition delays were obtained at room temperature. Qualitatively similar results were obtained at the Lewis laboratory.

Fourteen runs were conducted at temperatures from 110° F to -41° F at sea-level pressure. Except for run 79, all tests were made with hydrazine hydrate [lot b] and WFNA-2 [lot b]. The propellants used in run 79 were very similar in analyzed composition (hydrazine hydrate [lot a] and WFNA-2 [lot b]). The results of these experiments are shown in table V. A plot of ignition delay against temperature is shown in figure 12. The dotted lines enclose all the runs; the solid line indicates the average values. The ignition delays ranged from an average of 16 milliseconds at 110° F to approximately 146 milliseconds at -40° F. The reproducibility varied from about ± 1 millisecond at 110° to about ± 25 milliseconds at -10° F to even larger variations at lower temperatures. Ignition delays of the runs made at -10° F were greater than 50 milliseconds. Run 149 at -39° F resulted in an explosion that followed an extremely long ignition delay (> 631 milliseconds), and run 79 at -41° F yielded an inordinate delay of 131 milliseconds. For the latter run, the ignition point was difficult to determine and the full combustion pattern did not develop until more than 40 milliseconds after ignition.

Several Fuels with Various Nitric Acid Oxidants

In an effort to find a propellant combination that would have satisfactory ignition characteristics at least as low as -40° F, a series of experiments was conducted in which several fuels were tried with various nitric acid oxidants excluding mixed acid.

At sea-level pressure, 23 runs were conducted utilizing 6 fuels and 5 oxidants in 13 propellant combinations. All runs were made at about -40°F with one exception (run 67 at -75°F). The results of these experiments are shown in table VI.

Anhydrous nitric acid was tried with chemically pure furfuryl alcohol (runs 68, 69, and 73). Although ignition delay data were actually obtained for only one run (no camera timing marks for the others), superposition of the films from the three runs indicated similar delay periods. The measured delay for run 73 was 54 milliseconds. The ignition point was obscure, followed by a slow development of the combustion pattern (15 milliseconds long). After each run, objectionably large amounts of black carbonaceous combustion products were found deposited in the combustion chamber.

Turpentine, which has ignition properties that are excellent with mixed acid (reference 8) but poor with WFNA (reference 7), was tested with anhydrous nitric acid at -40°F (run 85). Ignition, after a long delay of 75 milliseconds, was followed in $1/2$ millisecond by an explosion. No additional runs were attempted.

A comparison of anhydrous nitric acid and hydrazine hydrate [lot a] with WFNA-2 [lot a] and hydrazine hydrate [lot a] at about -40°F is shown by runs 80 and 79. The delay with the anhydrous acid (48 milliseconds) was much shorter than the delay with the white fuming acid (131 milliseconds). The ignition point was indefinite and difficult to determine in each case.

Since both the furfuryl and mercapto groups appear to enhance ignition characteristics, combination of the two in a single fuel such as furfuryl mercaptan seemed promising. At -41°F , furfuryl mercaptan with WFNA-2 [lot a] had an ignition delay of only 23.4 milliseconds. With anhydrous nitric acid, it was even less (17.4 milliseconds). Besides short ignition delays, other advantages in the use of this fuel lie in its low initial freezing point ($< -112^{\circ}\text{F}$) and its low viscosity at low temperatures. A disadvantage is the objectionable residue found deposited in the combustion chamber after every run. The amount, however, is not as copious as that resulting from the use of furfuryl alcohol. Other disadvantages of the fuel are its present high cost and a very strong and disagreeable odor.

The mixed xylidines fuel was diluted with triethylamine to reduce its viscosity at low temperatures (table II). This fuel mixture was tested with several nitric acid oxidants as follows:

One run (run 67) was made at -75°F with WFNA-8 [6-KNO_3], which is WFNA-2 [lot a] to which potassium nitrate and water were added to depress its freezing point to -96°F . After a long ignition delay (> 262 milliseconds), an explosion occurred. Photographic views of the damage are shown in figure 13.

One run (run 84) was made at -40° F with WFNA-11 [4- HClO_4], which is WFNA-2 [lot a] to which perchloric acid was added to shorten the ignition delay and perchloric acid and water to depress its freezing point to -91° F. Ignition did not occur probably because of the high percentage of water in the acid.

Five runs resulting in ignitions were conducted at about -40° F with anhydrous nitric acid (runs 70, 71, 74, 78, and 81). Hard starts, indicated audibly and by photographic data, occurred in two of the runs without any resultant damage (runs 70 and 81). The average ignition delay for three of the runs was 35 milliseconds. No film speed timing marks were obtained for the other two runs. Three runs were made with the same fuel and WFNA-2 [lot a]. One (run 72), without timing marks, resulted in a hard start. The other two (runs 76 and 77) had average ignition delays of 42 milliseconds followed about 4 milliseconds later by explosions. Experiments with an open-cup-type apparatus (reference 7) with anhydrous nitric acid and WFNA-2 [lot a] yielded almost identical values of ignition delay. One run was made with WFNA-7. After an extremely long delay of 423 milliseconds, ignition occurred, followed 3 milliseconds later by an explosion.

A disadvantage of the mixed-xylydines - triethylamine mixture is its rapid increase in viscosity below -40° F. A more promising fuel was diallylaniline, also diluted by triethylamine to reduce its viscosity. This mixture, tested at -40° F with both anhydrous nitric acid and WFNA-2 [lot a], yielded excellent results. Two runs with WFNA-2 [lot a] (runs 90 and 91) had delays of 17.0 and 16.3 milliseconds, respectively. The two runs made with anhydrous nitric acid (runs 87 and 88) gave ignition delays of 13.5 and 14.7 milliseconds, respectively.

Diallylaniline - Triethylamine Mixture and

White Fuming Nitric Acid

In the search for a suitable ignitor fuel for use with the gasoline and white fuming nitric acid combination, the diallylaniline - triethylamine mixture was selected for an additional series of runs with white fuming nitric acid to determine ignition-delay temperature-pressure relationships with temperatures down to the lowest limit of serviceability of the acid.

At temperatures from 111° F to -60° F, 37 runs were conducted. Of these, 18 runs were made at sea-level pressure and the remainder at pressure altitudes of 77,400 to 88,300 feet. Four runs resulted in explosions, all at low initial ambient pressures. The results of these experiments are shown in table VII. A plot of ignition delay against temperature at the various pressures is shown in figure 14. With two exceptions,

the dotted lines enclose all runs that did not result in an explosion; the solid line indicates an average for these runs.

For the normal runs, the ignition delay varied from an average of about 9 milliseconds at 110° F to approximately 22 milliseconds at -50° F, regardless of initial ambient pressure. As in the other runs with nitric acid discussed previously, the low pressures of high altitude did not affect the values of ignition delay obtained at sea-level pressure.

Three of the four runs that resulted in explosions (runs 113, 116, and 121) had delays that were about 3 to 5 milliseconds longer than the average value at the temperature of the run. In each of these runs, the oxidant preceded the fuel into the combustion chamber. The fourth run (run 124) had an ignition delay that was in the normal range. In this run, the fuel entered the combustion chamber first.

All runs conducted at -50° F were made below the initial freezing point of the acid. Ignitions were obtained in all cases. The acid was either supercooled or, if the initial freezing point had been attained, the precipitated crystals in the acid solution did not interfere with the flow by clogging the injector holes. One run was made at -60° F (run 125; not shown in figure 14). An audibly weak ignition was obtained after a delay of 102 milliseconds. A copious semisolid slurry of nitric acid crystals and saturated solution found in the acid tank after the run indicated that the poor performance may have been caused by a high-water-content mother liquor being ejected into the combustion chamber.

Diallylaniline - Triethylamine Mixture and Special-Blend

Red Fuming Nitric Acid

Although the diallylaniline - triethylamine and white fuming nitric acid combination was found to be satisfactory with respect to ignition delay down to the freezing point of the acid, a fuel and oxidant were still needed that would ignite spontaneously at a pressure altitude of at least 45,000 feet and at temperatures as low as -95° F. A series of runs was conducted with the diallylaniline - triethylamine mixture and a low-freezing-point acid obtained by mixing several nitric acids and water (RFNA-4-16).

Eighteen runs were made at temperatures from 110° F to -95° F. With two exceptions, all runs were carried out at sea-level pressure. One low pressure run was made at each end of the temperature range, serving as checks for possible pressure effects on ignition delay. Run 140 (110° F) was conducted at a pressure altitude of 82,500 feet and run 133 (-95° F)

at 93,600 feet. The results of the experiments are shown in table VIII. A plot of ignition delay against temperature at the various pressures is shown in figure 15. There were no explosions in this series of runs.

The ignition delay varied from an average of about 13 milliseconds at 110° F to approximately 55 milliseconds at -95° F, again regardless of initial ambient pressure. In these runs, the flames in the combustion chamber were brighter and the exhaust noise was louder than with any other combination tested in this investigation. The light intensity and noise level increased with a decrease in temperature. Combustion-chamber deposits after a run were less than with any other combination tested except ones in which hydrazine hydrate was used as the fuel. The quantity of deposits decreased with a decrease in temperature.

The acid used in these runs is easily supercooled and difficult to freeze. All runs conducted below -88° F, the initial freezing point of the oxidant, were probably made with the acid in a supercooled state.

Effect on Ignition Delay of Variations in Time between

Propellant Entries into the Combustion Chamber

Most of the runs with aniline and red fuming nitric acid were made early in the investigation when the diaphragm-opening technique was still being developed and the time between jet entries into the combustion chamber varied over a wide range (0.3 to 75.2 milliseconds). This variance, however, did not seem to affect ignition delay values for the normal runs. A comparison of run 42 (68° F and 52,800 ft pressure altitude) and run 44 (69° F and 74,700 ft pressure altitude) shows ignition delays of 22.6 and 23.5 milliseconds, respectively (table IV); yet the acid entered the chamber 40.8 milliseconds before the aniline in the former run and the fuel preceded the oxidant by 3.0 milliseconds in the latter run.

Further evidences that moderate variations in propellant entry times have no significant effect on ignition delay were found throughout this investigation. An example is shown by two runs with the diallylaniline - triethylamine mixture and anhydrous nitric acid (runs 87 and 88, table VI) in which the oxidant preceded the fuel by 8.3 and 117.4 milliseconds, respectively. As mentioned previously, however, the lead of one propellant over another may have some influence on the production of explosions following ignition.

Effect of Water and NO₂ Content of Acid on Ignition Delay

Analysis of the data from the experiments yields some information on the effect of water and NO₂ content of the acid on ignition delay. For most of the runs in the aniline series, red fuming nitric acids from two lots were used without distinction (RFNA-4-29 and RFNA-5-35). In the particular NO₂ range of 29 to 35 percent, the 6-percent variation in NO₂ content of the acid had no significant effect on ignition delay as seen in figure 9. In these tests, the water contents of the two acids were essentially the same, differing by less than one percent.

In the experiments at -40° F with anhydrous nitric acid and white fuming nitric acid with various fuels, longer ignition delays were obtained with the white fuming acid than with the anhydrous acid in every case, as shown in the following table:

Fuel	Average ignition delay (milliseconds)	
	Anhydrous acid (0.2 percent H ₂ O, 2.5 percent NO ₂)	WFNA-2 [lot a] (1.8 percent H ₂ O, 0.5 percent NO ₂)
Hydrazine hydrate [lot a]	48	131
Mixed xyliidines - triethylamine mixture	35	42
Furfuryl mercaptan	17	23
Diallylaniline - triethylamine mixture	14	17

The longer delays with the white fuming acid may have been due either to the larger water content, to the smaller NO₂ content, or to both. With the mixed xyliidines - triethylamine mixture and several nitric acids (runs 74, 75, 76, 77, 78, and 81 of table VI), the ignition delay increased with an increase in water content and a simultaneous decrease in NO₂ content, as shown in figure 16 where ignition delay is plotted against water content and the NO₂ content of each acid is also indicated. Although variations in NO₂ content in the aniline series did not affect ignition delay, the same statement cannot be made for these cases because the NO₂ variations are in a different range. The effects of the two variables, therefore, cannot be evaluated separately for these conditions from the available data.

SUMMARY OF RESULTS

Ignition delay determinations of several fuels with nitric acid oxidants were made at simulated altitude conditions utilizing a small-scale rocket engine of approximately 50 pounds thrust. The results are summarized as follows:

1. With chemically pure aniline and red fuming nitric acid (29 to 35 percent NO_2 by weight), the ignition delays ranged from an average of about 18 milliseconds at 84°F to about 36 milliseconds at 30°F . Variations in initial ambient pressure from sea-level pressure to a pressure altitude of 88,300 feet for temperatures from 60 to 82°F had no significant effect on ignition delay. Five explosions occurred, the fuel preceding the oxidant into the combustion chamber in every case. With one exception, ignition delays of these abnormal runs were 4 to 13 milliseconds longer than the average normal values at the temperatures of the runs.

2. Acid ejected into a rocket chamber at low initial pressures changed rapidly from a spray into a solid stream because of a pressure rise above its vapor pressure. The pressure rise was probably caused by vaporization of the oxidant and evolution of initial reaction gases.

3. With hydrazine hydrate and white fuming nitric acid, the ignition delays ranged from an average of 16 milliseconds at 110°F to approximately 142 milliseconds at -40°F . One explosion occurred at -39°F .

4. Several fuels and nitric acid oxidants were screened at sea-level pressure and, with one exception, at about -40°F . The data are summarized in the following table:

Fuel	Oxidant	Average Ignition Delay (milliseconds)	Total number of runs	Explosions
Furfuryl alcohol	Anhydrous nitric acid	54	3	
Turpentine	Anhydrous nitric acid	75	1	1
Hydrazine hydrate	Anhydrous nitric acid	48	1	
Hydrazine hydrate	WFNA-2 [lot a]	131	1	
Furfuryl mercaptan	Anhydrous nitric acid	17	1	
Furfuryl mercaptan	WFNA-2 [lot a]	23	1	
Mixed xylidines - triethylamine mixture	WFNA-8 [6-KNO ₃]	>262	a ₁	1
Mixed xylidines - triethylamine mixture	WFNA-11 [4-HClO ₄]	b---	1	
Mixed xylidines - triethylamine mixture	Anhydrous nitric acid	35	5	
Mixed xylidines - triethylamine mixture	WFNA-2 [lot a]	42	3	2
Mixed xylidines - triethylamine mixture	WFNA-7	423	1	1
Diallylaniline - triethylamine mixture	Anhydrous nitric acid	14	2	
Diallylaniline - triethylamine mixture	WFNA-2 [lot a]	17	2	

^aConducted at -75° F.

^bNo ignition.

The combination that ignited most rapidly was a diallylaniline - triethylamine mixture and anhydrous nitric acid, yielding an average ignition delay of about 14 milliseconds.

5. With a mixture of 57 percent diallylaniline and 43 percent triethylamine (by weight) and white fuming nitric acid, the ignition delays varied from an average of about 9 milliseconds at 110° F to

approximately 22 milliseconds at -50° F, regardless of initial ambient pressure variations from sea-level pressure to a pressure altitude of 88,300 feet. Four runs resulted in explosions.

6. With a mixture of 57 percent diallylaniline and 43 percent triethylamine (by weight) and red fuming nitric acid containing 3.5 percent water and 16 percent nitrogen dioxide (by weight), the ignition delays varied from an average of about 13 milliseconds at 110° F to approximately 55 milliseconds at -95° F, regardless of initial ambient pressure variations from sea-level pressure to a pressure altitude of 93,600 feet. All runs resulted in satisfactory starts; no explosions were experienced.

7. In all the experiments, wide variations in time between propellant entries into the combustion chamber had no apparent effect on ignition delay.

8. With aniline and red fuming nitric acids with essentially equal water contents, a variation in the NO_2 content of the acid from 29 to 35 percent had no significant effect on ignition delay. With other fuels and nitric acids, a decrease in the NO_2 content from 2.5 to 0.5 percent accompanied by a simultaneous increase in the water content from 0.2 to 1.8 percent increased the ignition delay.

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TABLE I. - ANALYSES OF NITRIC ACID OXIDANTS

Acid	Runs	HNO ₃	NO ₂	H ₂ O ^a	Other components
		Percent by weight			
^b RFNA-0-20		80.7	19.5	0	
RFNA-0-22	154, 156	78.2	22.0	0	
^b RFNA-0-25		74.9	24.9	0.2	
RFNA-4-16	126-143	80.5	16.0	3.5	
		^c 79.9	^c 16.5	^c 3.6	
RFNA-4-29	^d [42-65] , 152, 155	67.1	28.6	4.3	
RFNA-5-35	^d [42-65], 153	60.1	34.7	5.2	
WFNA-2 [lot a]	72, 76, 77, 79, 83, 89-125	97.7	0.5	1.8	
WFNA-2 [lot b]	144-151, 157- 160, 165	97.4	0.7	1.9	
WFNA-7	75	93.0	0.2	6.8	
WFNA-8 [6-KNO ₃]	67	^c 85.9	^c 0.4	^c 7.7	KNO ₃
					^c 6.0
WFNA-11 [4-HClO ₄]	84	^c 85.0	^{c, e} 0.4	^c 10.5	HClO ₄
					^c 4.1
Anhydrous nitric acid	68-71, 73, 74, 78, 80-82, 85-88	97.3	2.5	0.2	
^{b, f} Anhydrous nitric acid		97.1	2.6	0.3	

^aBy difference.^bUsed in the preparation of RFNA-4-16.^cCalculated.^dRFNA-4-29 and RFNA-5-35 used in bracketed runs without distinction.^eColorless solution indicated NO₂ reaction with HClO₄.^fSame anhydrous acid as above but used at a later date.

TABLE II - PHYSICAL PROPERTIES OF FUELS

Fuel	Runs	Viscosity (centistokes)					Initial freezing point (°F)	Density (g/ml)	
		^a 110° F	77° F	-40° F	-70° F	^a -95° F		68° F	-40° F
Aniline	42-66, 152-156	2.26	3.72	-----	-----	-----	19	1.021	-----
Furfuryl alcohol	68, 69, 73	2.80	4.50	219.1	-----	-----	-----	1.146	1.201
Furfuryl mercaptan	82, 83	.92	1.18	6.02	^a 14.3	40.0	< -112	1.126	1.191
^b Turpentine	85	1.34	1.73	8.52	^a 18.8	46.5	< -112	0.868	0.919
^c Hydrazine hydrate [lot a]	79, 80								
^d Hydrazine hydrate [lot b]	144-151, 157-160, 165, 166	-----	1.67	-----	-----	-----	-----	1.031	-----
^e Triethylamine		.44	.51	1.18	1.67	2.43	< -112	0.731	0.784
^e Mixed xylidines		2.30	4.00	761	^a 30,000	-----	-----	0.978	1.027
^e Diallylaniline		1.88	2.97	150.6	^a 2,000	-----	-----	0.955	1.003
^f Mixed xylidines - triethylamine mixture	67, 70-72, 74-78, 81, 84, 86	1.01	1.40	17.83	90.91	800	< -112	0.873	0.926
^g Diallylaniline - triethylamine mixture	87-143	.81	1.06	5.81	^a 14.5	47	< -112	0.851	0.903

^aExtrapolated.^bCommercial gum turpentine.^cActually analyzed as 64.2 percent hydrazine, 35.6 percent water, and 0.2 percent ammonia (by weight).^dActually analyzed as 65.3 percent hydrazine, 34.7 percent water, and 0.0 percent ammonia (by weight).^eUsed in preparation of fuel mixtures.^f50 percent mixed xylidines and 50 percent triethylamine (by volume at room temperature).^g57 percent diallylaniline and 43 percent triethylamine (by weight).

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TABLE III - PHYSICAL PROPERTIES OF NITRIC ACID OXIDANTS

Acid	Viscosity (centistokes)					Approximate initial freezing point (°F)	Density (g/ml)	
	^a 110° F	77° F	-40° F	^a -70° F	^a -95° F		68° F	-40° F
RFNA-0-22	0.730	0.951	5.40	14.5	-----	-74	1.5978	1.695
RFNA-4-16	0.724	0.953	6.04	17.8	^b 70.0	-88	1.5577	
RFNA-4-29	0.850	1.15	10.56	40.5	238	^c ---	1.5784	1.680
WFNA-2[lot a]	0.470	0.582	2.32	----	-----	-46	1.4975	1.602
WFNA-2[lot b]	0.437	0.534	2.01	----	-----	-47	1.5043	1.606
WFNA-7	0.554	0.709	3.42	8.3	-----	-69	1.4863	1.588
WFNA-8[6-KNO ₃]	0.755	1.01	7.61	26.0	128	-96	1.5250	
WFNA-11[4-HClO ₄]	0.609	0.786	3.91	9.4	^b 28.2	-91	1.5075	1.598
Anhydrous nitric acid	0.452	0.555	2.09	----	-----	-45	1.5145	1.616

^aExtrapolated.^bSupercooled.^cSupercooled to approximately -170° F without freezing.

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TABLE IV - SUMMARY OF DATA FOR CHEMICALLY PURE ANILINE AND RED FUMING NITRIC ACID WITH 29 TO 35 PERCENT (BY WEIGHT) NITROGEN DIOXIDE

Run	Average propellant tempera- ture (°F)	Initial pressure altitude (ft)	Initial ambient pressure (mm Hg)	Maximum combustion- chamber pressure (lb/sq in. gage)	Time to attain maximum combustion- chamber pressure (sec)	Temperatures (°F)						Lead pro- pellant into com- bustion chamber	Time between jet entries into com- bustion chamber (milli- seconds)	Ignition delay (milli- seconds)	Time between ignition and exple- sion or burn-out (milli- seconds)
						Fuel	Oxidant	Injector head	Con- stant temper- ature bath	Nozzle plate	Ambient air				
55	a88	81,600	19.2	292	2.4	a88	a88	a88	---	a88	a88	Fuel	23.2	24.6	b, c, ---
46	a82	0	760	b---	---	a82	a82	a82	---	a82	a82	Fuel	14.0	28.4	b1.5
54	a82	81,800	19.0	284	3.2	a82	a82	a82	---	a82	a82	Fuel	51.2	20.8	---
48	a80	30,700	84.6	287	3.1	a80	a80	a80	---	a80	a80	Oxidant	26.3	19.7	---
58	a79	72,200	30.2	d---	---	a79	a79	a79	---	a79	a79	Fuel	19.1	26.7	d7.9
49	a78	40,700	92.8	b---	---	a78	a78	a78	---	a78	a78	Fuel	44.1	19.0	b1.4
47	a75	0	760	b---	---	a75	a75	a75	---	a75	a75	Fuel	.5	33.8	b6.7
50	a73	0	760	b---	---	a73	a73	a73	---	a73	a73	Fuel	23.6	25.4	b1.0
52	a72	72,400	30.0	258	3.3	a72	a72	a72	---	a72	a72	Oxidant	55.6	22.9	---
51	a70	0	760	290	2.8	a70	a70	a70	---	a70	a70	Fuel	10.0	23.8	---
53	a70	69,200	35.0	284	2.8	a70	a70	a70	---	a70	a70	Oxidant	75.2	24.2	---
153	70	0	760	a272	f1.3	70	70	70	70	72	75	Oxidant	1.7	20.4	---
155	70	0	760	273	1.8	70	70	71	70	73	78	Oxidant	5.0	21.6	---
44	a68	74,700	26.8	255	3.5	a68	a68	a68	---	a68	a68	Fuel	3.0	23.5	---
42	a68	82,800	76.3	285	2.0	a68	a68	a68	---	a68	a68	Oxidant	40.8	22.6	---
43	a68	88,300	14.0	282	2.9	a68	a68	a68	---	a68	a68	Oxidant	57.8	21.6	---
59	61	0	760	a153	f1.5	61	---	61	60	68	78	Oxidant	37.7	25.5	---
64	61	0	760	245	2.8	62	61	62	59	77	85	Oxidant	39.5	26.4	---
57	80	0	760	298	3.0	80	60	61	61	64	76	Fuel	3.1	24.2	---
62	60	80,100	20.8	280	2.8	60	60	61	61	69	77	Fuel	5.9	28.2	---
65	30	0	780	a216	f5.4	51	30	30	30	70	78	Oxidant	24.2	36.4	---

^aThermometer-indicated temperature near apparatus.

^bExplosion.

^cApparatus was damaged, but combustion chamber remained intact.

^dCombustion chamber burned out at injector head.

^ePeak pressure; maximum pressure possible was probably not attained.

^fTime to attain peak combustion-chamber pressure.

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TABLE V - SUMMARY OF DATA FOR HYDRAZINE HYDRATE AND WHITE FUMING NITRIC ACID (USAF SPECIFICATION NO. 14104)

Run (a)	Average propellant temperature (°F)	Initial pressure altitude (ft)	Peak combustion chamber pressure (lb/sq in. gage) (b)	Time to attain peak combustion-chamber pressure (sec)	Temperatures (°F)						Lead propellant into combustion chamber	Time between jet entries into combustion chamber (milli-seconds)	Ignition delay (milli-seconds)
					Fuel	Oxidant	Injector head	Constant temperature bath	Nozzle plate	Ambient air			
144	110	0	c---	---	110	110	111	111	73	79	Oxidant	1.3	17.0
159	110	0	c 237	2.5	110	110	111	111	86	89	Oxidant	6.3	15.3
145	80	0	174	2.7	80	80	80	80	89	71	Oxidant	0.3	19.1
151	80	0	216	2.5	80	80	80	81	70	73	Oxidant	.9	16.7
146	50	0	170	2.7	51	50	52	52	84	68	Oxidant	1.8	23.6
158	50	0	227	2.6	50	50	51	51	71	77	Oxidant	4.6	26.2
147	20	0	192	2.6	21	20	20	20	54	61	Oxidant	7.8	29.6
150	20	0	235	2.5	21	20	23	24	53	65	Fuel	3.0	50.1
148	-9	0	181	2.4	-10	-9	-9	-4	51	62	Fuel	8.9	59.5
157	-10	0	224	2.3	-10	-10	-7	-10	60	65	Fuel	.9	104.7
160	-10	0	179	2.2	-10	-9	-9	-10	56	60	Fuel	.6	70.2
165	-10	0	220	2.2	-10	-10	-8	-9	60	63	Oxidant	.5	54.4
149	-39	0	d---	---	-39	-39	-39	-40	48	80	e-----	<0.3	f>631
E79	-41	0	139	5.0	-41	-41	-37	-41	55	59	Oxidant	22.4	130.7

^aAll runs (except run 79) made with hydrazine hydrate [lot b] and WFNA-2 [lot b].

^bMaximum pressure possible was probably not attained.

^cClogged combustion-chamber pressure tap.

^dExplosion.

^eBoth propellants entered the combustion chamber in the same motion picture frame.

^fIgnition point and subsequent explosion not recorded.

^gRun made with hydrazine hydrate [lot a] and WFNA-2 [lot a].

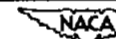


TABLE VI - SUMMARY OF DATA FOR SEVERAL FUELS AND NITRIC ACID OXIDANTS AT LOW TEMPERATURES AND SEA-LEVEL PRESSURE

Run	Fuel (a)	Oxidant (b)	Average propellant temperature (°F)	Initial pressure altitude (ft)	Maximum combustion- chamber pressure (lb/sq in. gage)	Time to attain maximum combustion- chamber pressure (sec)	Temperatures (°F)						Lead pro- pellant into com- bustion chamber	Time between jet entries into com- bustion chamber (milli- seconds)	Ignition delay (milli- seconds)	Time between ignition and explo- sion (milli- seconds)
							Fuel	Oxidant	Injector head	Constant temper- ature bath	Nozzle plate	Ambient air				
68	Furfuryl alcohol	Anhydrous nitric acid	-40	0	48	4.9	-40	-40	-34	-41	53	75	Oxidant	0.0	0.0	---
69	Furfuryl alcohol	Anhydrous nitric acid	-41	0	d---	---	-41	-41	-35	-41	57	78	Oxidant	0.0	0.0	---
70	Furfuryl alcohol	Anhydrous nitric acid	-40	0	*170	5.4	-40	---	-35	-41	54	65	Oxidant	65.5	53.7	---
85	Turpentine	Anhydrous nitric acid	-40	0	---	---	-39	-41	-38	-39	60	75	Oxidant	79.8	74.7	0.5
80	Hydrazine hydrate [lot a]	Anhydrous nitric acid	-40	0	---	---	-40	-40	-35	-38	52	67	Oxidant	38.4	148.8	---
79	Hydrazine hydrate [lot a]	WFNA-2 [lot a]	-41	0	*159	5.0	-41	-41	-37	-41	55	59	Oxidant	22.4	150.7	---
82	Furfuryl mercaptan	Anhydrous nitric acid	-40	0	200	2.7	-39	-40	-35	-38	52	68	Fuel	33.5	17.4	---
83	Furfuryl mercaptan	WFNA-2 [lot a]	-41	0	*104	2.5	-41	-41	-38	-40	54	71	Oxidant	20.2	25.4	---
67	MX-TFA ^k	WFNA-6 [8-KNO ₃]	-75	0	---	---	-75	-77	-68	-73	69	80	Oxidant	68.5	282	---
84	MX-TFA	WFNA-11 [4-HClO ₄]	-40	0	d---	---	---	-40	-37	-41	41	55	Oxidant	77.5	No ignition	---
70	MX-TFA	Anhydrous nitric acid	-39	0	d---	---	-39	-39	-41	-40	71	81	Oxidant	0.0	0.1	---
71	MX-TFA	Anhydrous nitric acid	-39	0	306	3.7	-39	-39	-40	-40	68	79	Fuel	0.0	0.0	---
74	MX-TFA	Anhydrous nitric acid	-41	0	290	5.7	---	-41	-36	-39	58	64	Oxidant	18.1	29.6	---
73	MX-TFA	Anhydrous nitric acid	-39	0	*254	4.9	-38	-39	-35	-51	44	49	Oxidant	25.2	39.4	---
81	MX-TFA	Anhydrous nitric acid	-40	0	294	3.8	-38	-41	-35	-55	51	67	Oxidant	4.4	137.6	---
72	MX-TFA	WFNA-2 [lot a]	-41	0	d---	---	-41	-41	-42	-41	59	71	Oxidant	0.0	0.1	---
76	MX-TFA	WFNA-2 [lot a]	-40	0	---	---	-39	-40	-35	-38	63	75	Oxidant	2.2	41.5	4.0
77	MX-TFA	WFNA-2 [lot a]	-40	0	---	---	-40	-40	-35	-38	54	61	Fuel	5.0	43.0	3.8
75	MX-TFA	WFNA-7	-40	0	---	---	-39	-40	-55	-39	44	52	Fuel	12.2	425.3	3.1
87	DAA-TFA ^m	Anhydrous nitric acid	-41	0	288	4.1	-41	---	-40	-48	44	67	Oxidant	8.3	15.5	---
88	DAA-TFA	Anhydrous nitric acid	-40	0	*192	2.7	-38	-42	-37	-39	55	67	Oxidant	117.4	14.7	---
90	DAA-TFA	WFNA-2 [lot a]	-40	0	300	4.4	-40	-40	-40	-39	52	61	Oxidant	1.8	17.0	---
91	DAA-TFA	WFNA-2 [lot a]	-41	0	*305	5.1	-41	-41	-57	-41	48	---	Oxidant	8.6	18.3	---

^aSee table II for physical properties.^bSee table I for analyses and table III for physical properties.^cNo timing marks on film.^dFrozen combustion-chamber pressure tap.^ePeak pressure; maximum pressure possible was probably not attained.^fTime to attain peak combustion-chamber pressure.^gExplosion.^hNo proper record.ⁱApproximate value. Ignition point difficult to determine.^jIgnition and explosion occurred after end of film roll.^kMixed xylydines - triethylamine mixture.^lHard start. No resultant damage.^mDiallylaniline - triethylamine mixture.

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TABLE VII - SUMMARY OF DATA FOR 57 PERCENT DIALLYLANILINE AND 43 PERCENT TRIETHYLAMINE (BY WEIGHT), AND WHITE FUMING NITRIC ACID
(USAF SPECIFICATION NO. 14104)

Run	Average propellant temperature (°F)	Initial pressure altitude (ft)	Initial ambient pressure (mm Hg)	Maximum combustion- chamber pressure (lb/sq in. gage)	Time to attain maximum combustion- chamber pressure (sec)	Temperatures (°F)					Lead pro- pellant into com- bustion chamber	Time between jet entries into com- bustion chamber (milli- seconds)	Ignition delay (milli- seconds)	Time between ignition and explo- sion (milli- seconds)	
						Fuel	Oxidant	Injector head	Constant tempera- ture bath	Nozzle plate					Ambient air
111	111	0	760	283	5.0	---	111	111	111	77	85	Oxidant	5.1	9.2	---
124	111	86,400	15.3	a---	---	112	111	112	113	72	77	Fuel	.9	9.9	0.9
116	110	78,200	22.5	a---	---	110	110	110	110	76	79	Oxidant	.6	11.4	.3
117	109	77,400	23.5	b288	05.5	109	109	110	110	75	82	Fuel	.3	10.3	---
115	104	0	760	284	5.4	104	104	105	105	72	75	Oxidant	2.1	7.8	---
98	80	0	760	277	4.3	80	81	81	78	70	77	Oxidant	2.6	10.9	---
102	80	82,800	18.2	302	4.6	80	80	81	79	69	72	Oxidant	.3	10.5	---
107	80	81,600	19.2	288	4.9	80	81	81	81	74	74	d---	<.3	11.0	---
99	79	0	760	b187	02.9	79	79	79	80	74	77	Oxidant	2.6	10.2	---
96	50	0	760	303	4.8	---	50	51	50	69	71	Oxidant	2.2	9.8	---
97	50	0	760	245	3.6	---	50	50	52	86	75	Oxidant	3.6	11.0	---
101	50	0	760	295	5.0	50	50	51	50	86	71	d---	<.3	12.8	---
106	50	81,000	19.8	297	4.9	50	50	50	52	52	73	Fuel	1.0	11.6	---
112	50	80,600	20.1	280	4.6	---	---	---	---	68	---	Fuel	.3	11.8	---
110	21	85,100	16.5	b222	04.6	21	21	20	18	63	69	Fuel	0.3	14.2	---
94	20	0	760	304	4.7	19	20	20	19	62	64	Oxidant	1.3	13.4	---
95	20	0	760	302	4.1	20	21	21	19	61	65	Oxidant	1.9	13.8	---
105	20	80,700	20.0	b297	05.1	20	20	20	20	51	54	d---	4.3	20.6	---
92	-9	0	760	305	4.4	-9	-9	-9	-9	43	58	Oxidant	5.9	15.1	---
93	-9	0	760	278	4.1	-9	-9	-9	-9	42	54	Oxidant	3.5	11.5	---
100	-10	0	760	b300	05.1	-10	-10	-10	-9	84	69	Oxidant	1.0	14.2	---
105	-10	81,800	19.0	f---	---	-10	-10	-10	-9	49	64	Oxidant	.7	14.6	---
113	-10	78,100	22.6	a---	---	-10	-11	-8	-9	48	53	Oxidant	1.3	17.7	2.5
121	8-10	84,000	17.2	a---	---	---	---	-8	-10	57	64	Oxidant	1.3	19.2	3.5
123	-11	80,400	20.5	f---	---	-11	-11	-8	-8	51	54	Oxidant	1.0	15.5	---
104	-32	84,800	18.5	f---	---	-39	-39	-39	-39	45	49	Oxidant	0.7	18.0	---
89	-40	0	760	303	h---	-40	-40	-43	-41	42	67	Oxidant	h---	h---	---
80	-40	0	760	300	4.4	-40	-40	-40	-39	52	61	Oxidant	1.9	17.0	---
122	-40	80,700	20.0	f---	---	-40	-40	-40	-39	59	65	Oxidant	.6	20.6	---
91	-41	0	760	b303	05.1	-41	-41	-37	-41	48	---	Oxidant	6.6	16.3	---
114	-42	80,200	20.5	b278	05.2	-41	-43	-37	-41	51	33	Oxidant	.3	20.5	---
108	-50	0	760	300	4.9	-50	-50	-50	-48	---	64	Oxidant	2.6	25.5	---
109	-50	0	760	f---	---	-50	-50	-51	-53	---	51	Oxidant	1.6	21.8	---
118	-50	87,500	14.5	i---	---	-51	-50	-48	-47	50	54	i-----	i---	i---	---
119	-50	88,300	14.0	f---	---	-51	-50	-48	-50	52	53	Fuel	1.6	24.4	---
120	-50	84,100	17.1	f---	---	-51	-50	-47	-48	53	56	Fuel	2.2	21.4	---
125	-80	0	760	37	h---	-62	-58	-57	-60	45	50	Fuel	34.2	102.4	---

^aExplosion.

^bPeak pressure; maximum pressure possible was probably not attained.

^cTime to attain peak combustion-chamber pressure.

^dBoth propellants entered the combustion chamber in the same motion picture frame.

^eTemperature of coolant in blending chamber.

^fFrozen combustion-chamber pressure tap.

^gTemperature of constant temperature bath.

^hNo time record.

ⁱNo photographic or combustion-chamber pressure records.

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TABLE VIII - SUMMARY OF DATA FOR 57 PERCENT DIALLYLANILINE AND 43 PERCENT TRIETHYLAMINE (BY WEIGHT), AND RED FUMING NITRIC ACID CONTAINING 3.5 PERCENT WATER AND 16 PERCENT NITROGEN DIOXIDE (BY WEIGHT)

Run	Average propellant tempera- ture (° F)	Initial pressure altitude (ft)	Initial ambient pressure (mm Hg)	Peak combustion- chamber pressure (lb/sq in. gage) (a)	Time to attain peak combustion- chamber pressure (sec)	Temperatures (° F)						Lead pro- pellant into com- bustion chamber	Time between jet entries into com- bustion chamber (milli- seconds)	Ignition delay (milli- seconds)
						Fuel	Oxidant	Injector head	Con- stant temper- ature bath	Nozzle plate	Ambient air			
139	110	0	760	231	2.7	110	109	111	111	68	76	Oxidant	1.1	13.6
140	110	82,500	18.5	231	2.3	110	110	110	109	71	81	Fuel	2.2	11.1
142	79	0	760	228	2.7	79	79	79	78	--	70	Fuel	4.2	17.0
138	50	0	760	257	2.7	50	49	51	51	58	58	Fuel	.6	16.7
141	20	0	760	264	2.8	21	19	27	26	58	62	Fuel	9.3	22.3
137	-9	0	760	258	2.8	-9	-8	-8	-9	49	52	Fuel	1.3	26.3
136	-40	0	760	249	2.7	-40	-40	-38	-39	42	46	Oxidant	.9	31.2
126	-41	0	760	274	2.8	-41	-41	-38	-41	44	56	Oxidant	.3	29.9
127	-60	0	760	b---	---	-80	-61	-55	-57	47	45	Oxidant	2.8	43.3
135	-80	0	760	256	3.0	-59	-60	-54	-58	35	45	Oxidant	2.5	38.2
128	-70	0	760	268	2.8	-69	-71	-61	-63	43	50	Oxidant	.8	40.9
134	-70	0	760	243	2.8	-89	-71	-80	-61	36	48	Fuel	.6	42.0
129	-80	0	760	260	2.8	-80	-80	-72	-81	41	58	Fuel	6.1	46.7
130	-90	0	760	268	2.9	-90	-90	-78	-91	44	80	Oxidant	0.3	65.9
143	-90	0	760	177 ^c	3.1	-80	-90	-79	---	36	48	Oxidant	3.4	51.1
131	-95	0	760	235	2.8	-95	-96	-89	-97	34	42	Fuel	2.9	53.9
132	-95	0	760	253	3.0	-95	-95	-85	-95	41	50	Fuel	.8	58.5
133	-95	83,600	10.9	250	2.8	-85	-95	-87	-95	41	64	Oxidant	.6	53.4

^aMaximum pressure possible was probably not attained.^bFrozen combustion-chamber pressure tap.^cCombustion-chamber pressure tap found clogged after run.

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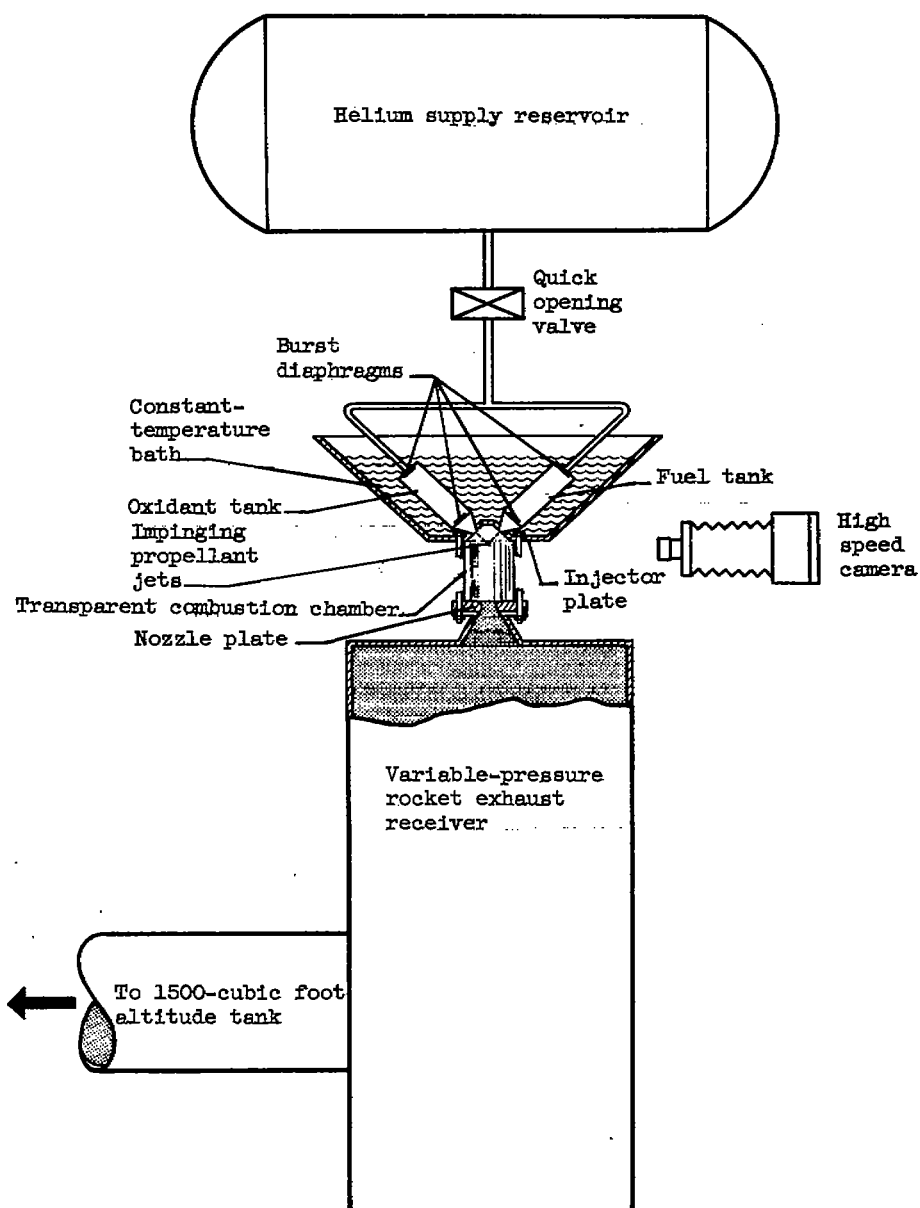


Figure 1. - Diagrammatic sketch of ignition-delay apparatus.

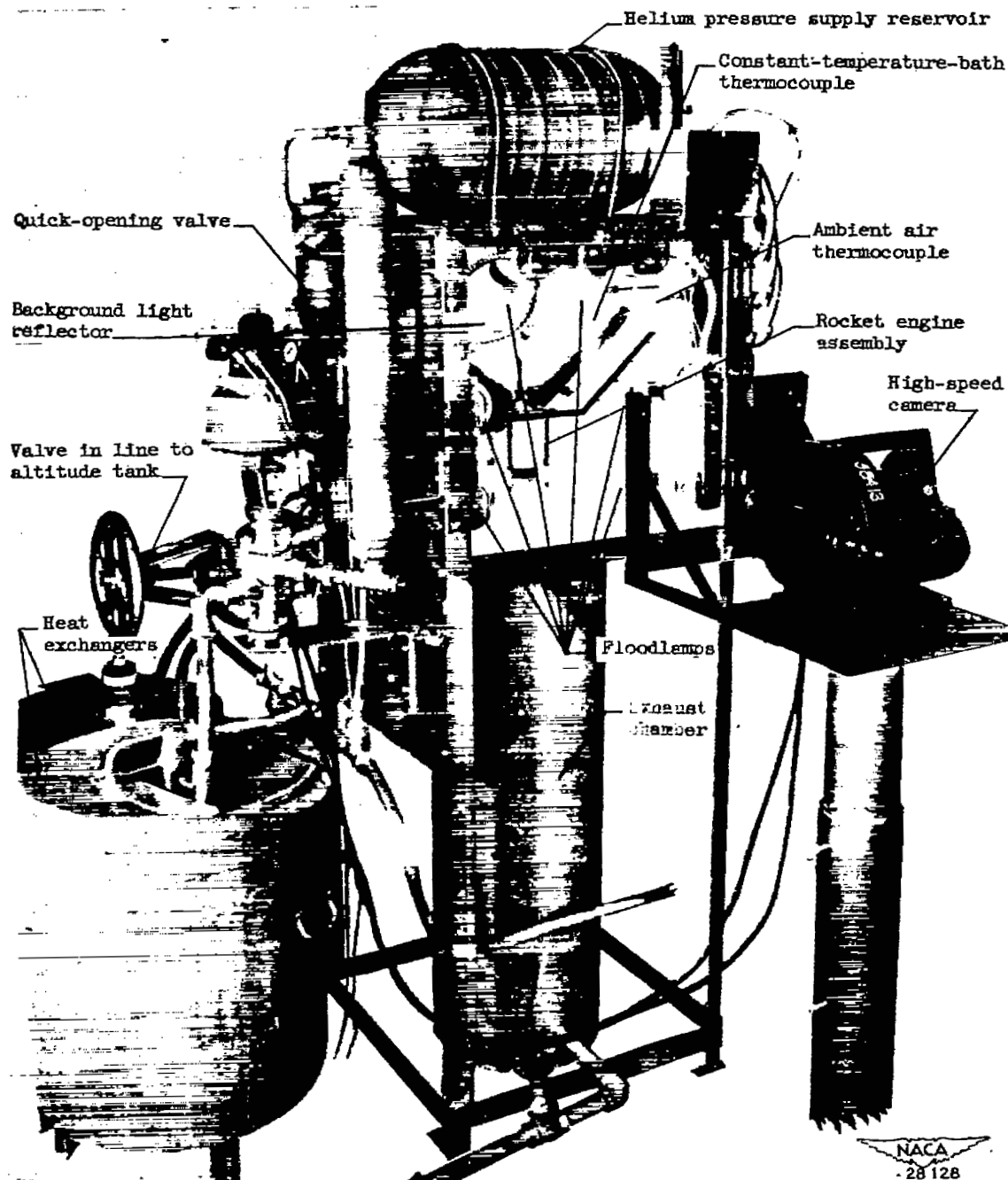


Figure 2. - Ignition delay apparatus.

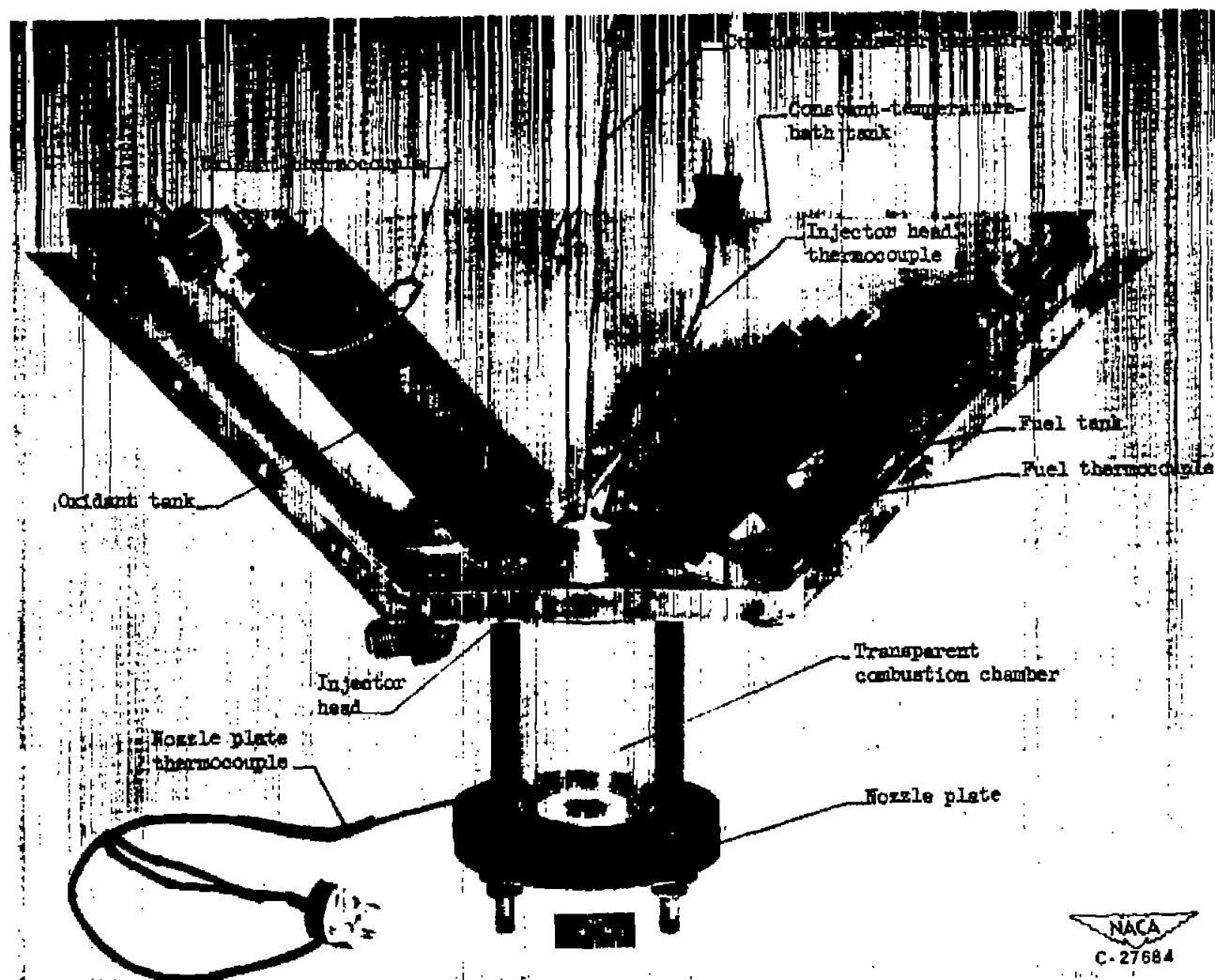


Figure 3. - Assembly of small-scale rocket engine used in ignition delay apparatus.

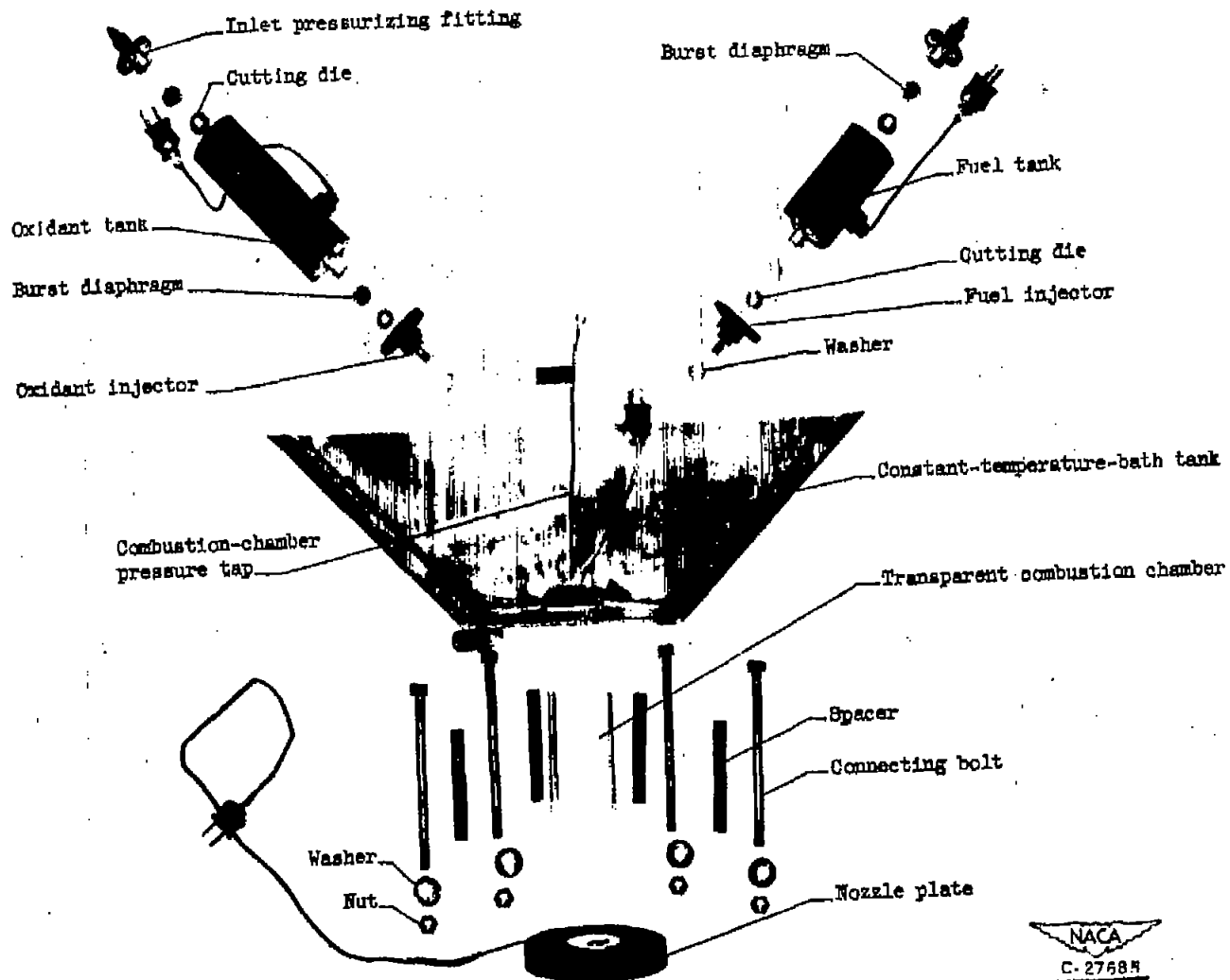


Figure 4. - Exploded view of small-scale rocket engine used in ignition delay apparatus.

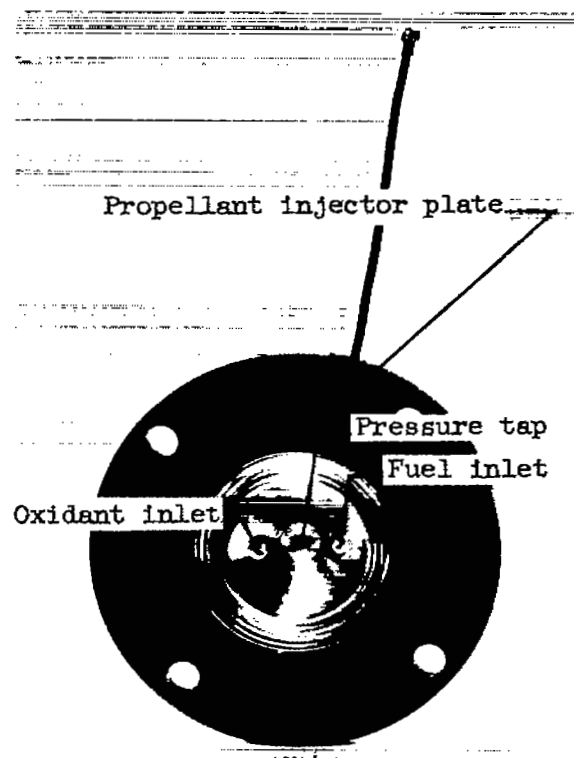


Figure 5. - Injector head assembly

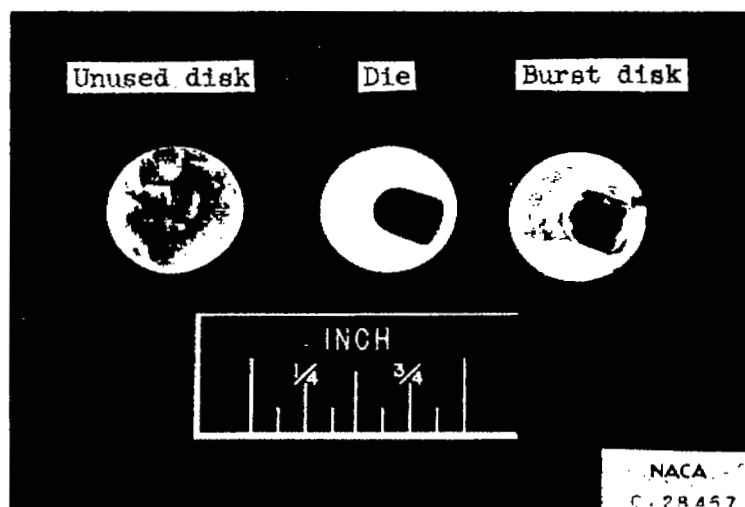


Figure 6. - One type of bursting diaphragm and cutting die used in propellant tanks of small-scale rocket engine.



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Figure 7. - High-speed photographs of typical run.

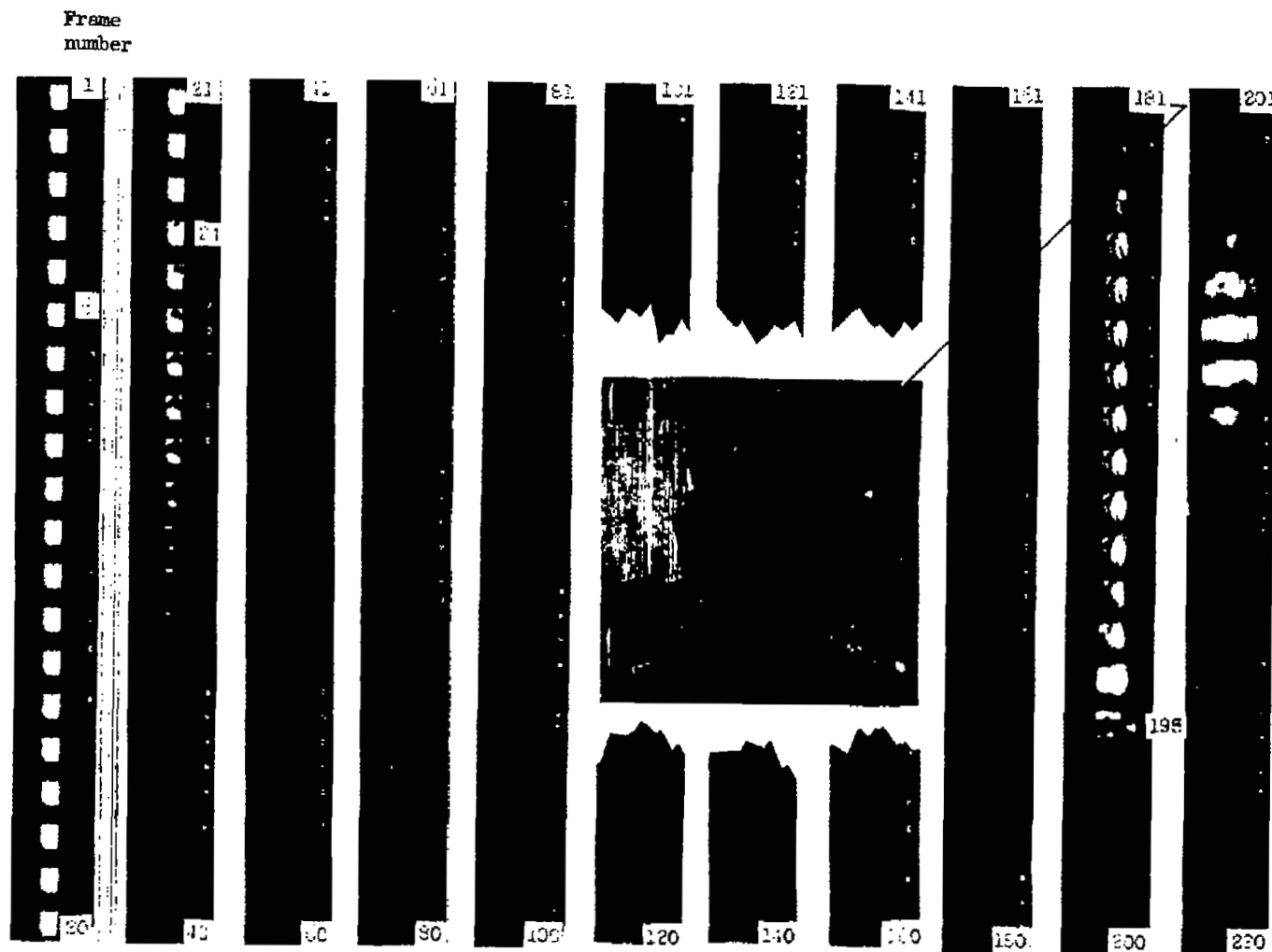


Figure 8. - High-speed photographs of run resulting in explosion (run 77).



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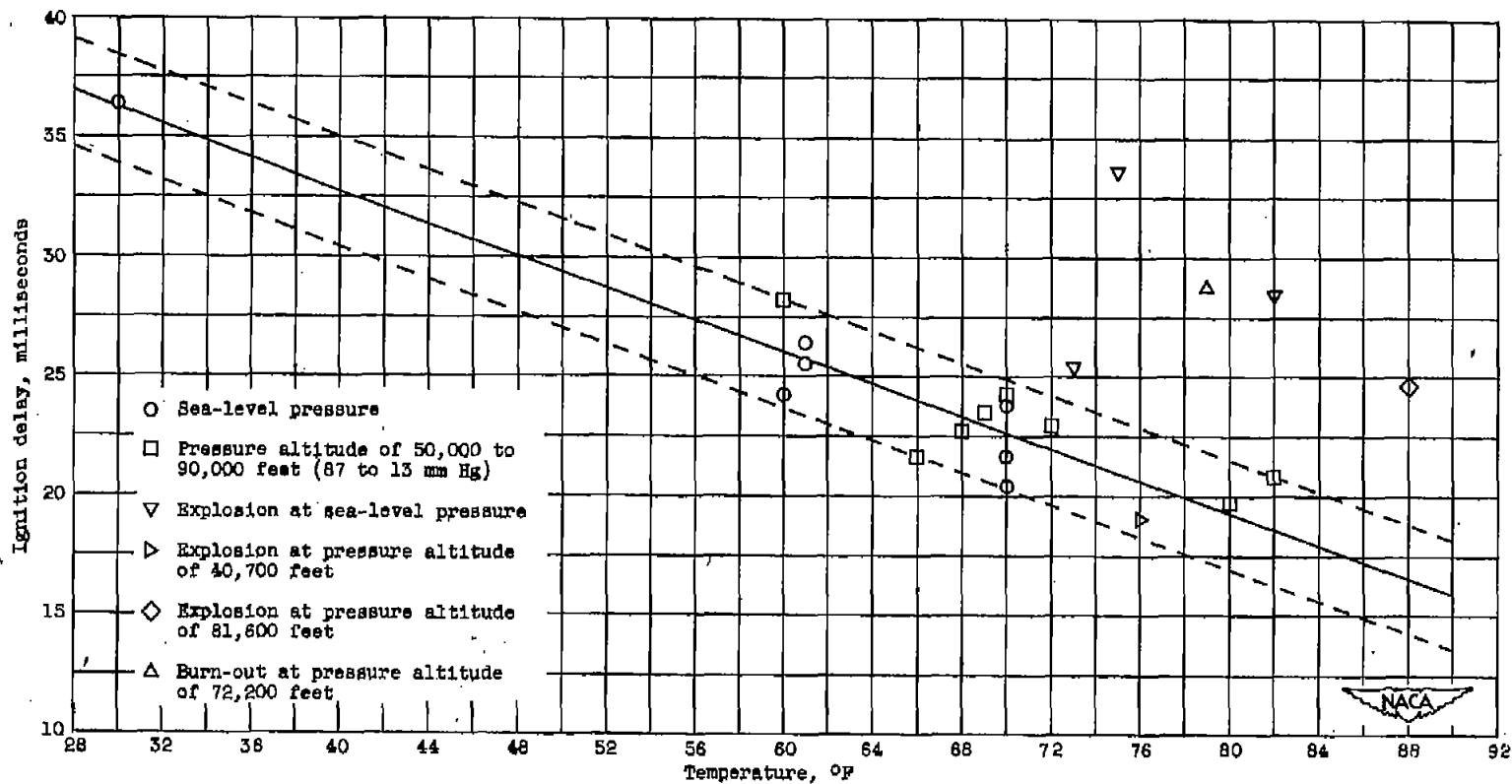
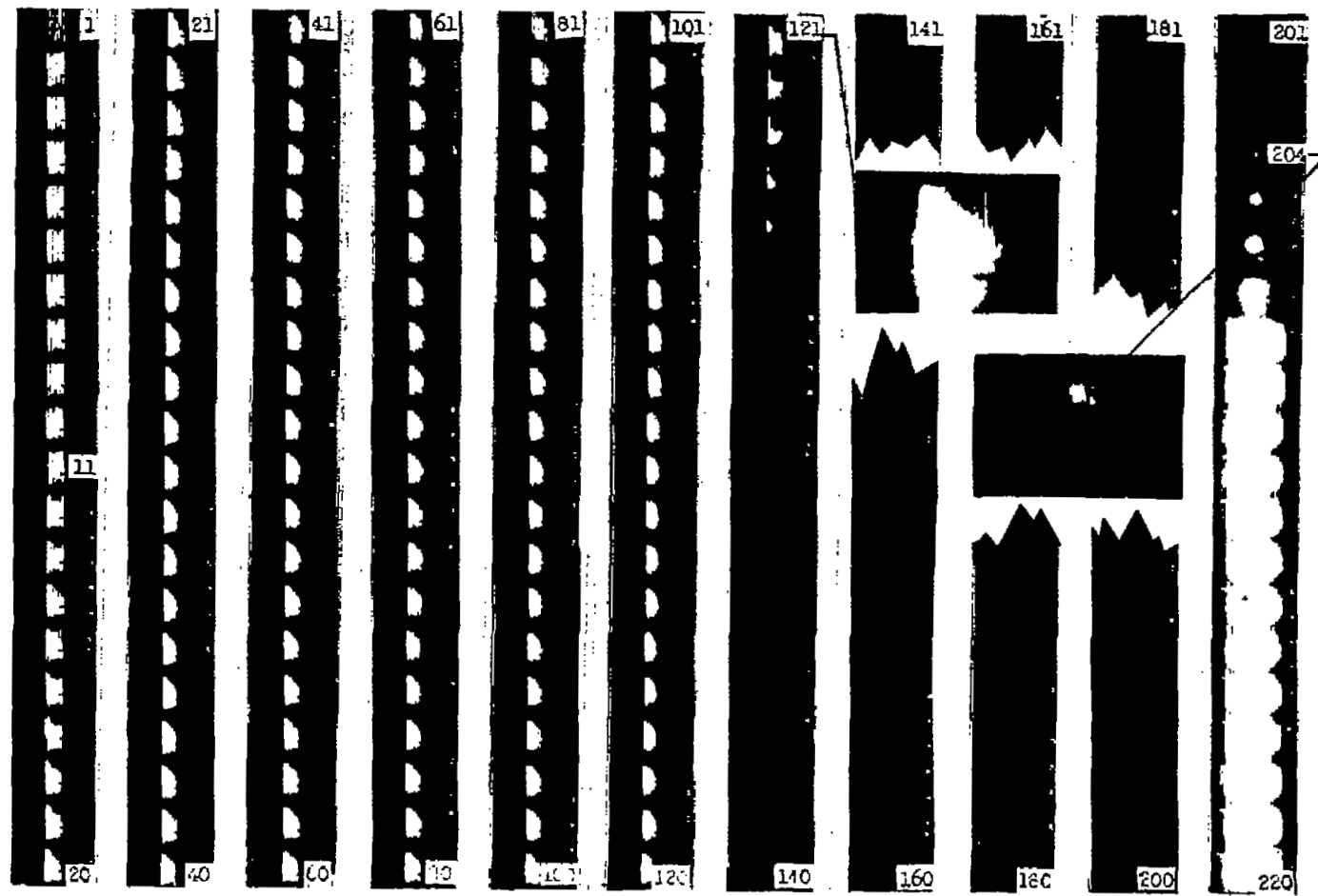


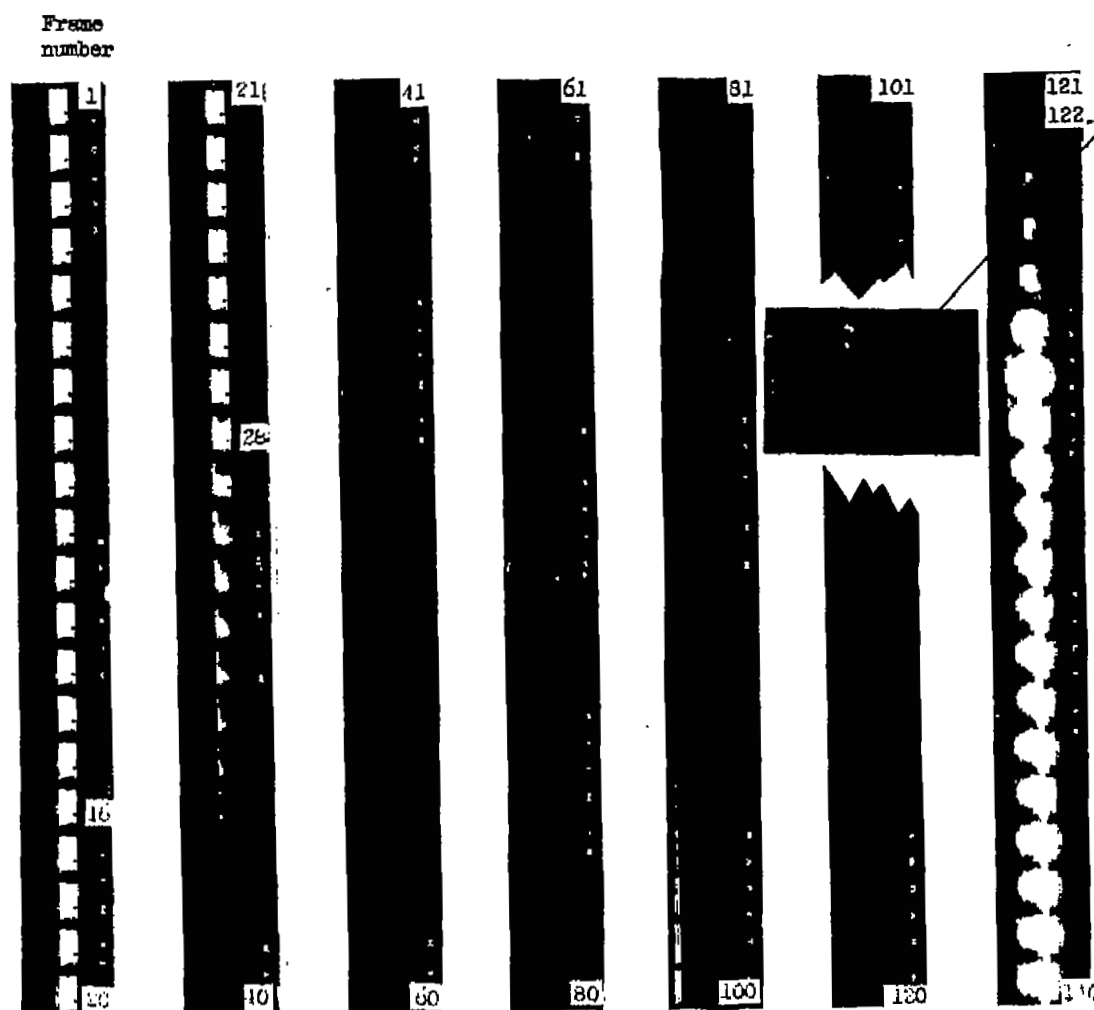
Figure 9. - Ignition delay of chemically pure aniline and red fuming nitric acid with 29 to 35 percent nitrogen dioxide (by weight).

Frame
number



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Figure 10. - High-speed photographs of run 45 showing transformation of diffuse oxidant spray into normal solid stream before entry of fuel jet. Reference arrow projects from the fuel inlet side of chamber.



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Figure 11. - High-speed photographs of run 44 showing normal ignition delay when fuel precedes oxidant into combustion chamber at low initial ambient pressure. Reference arrow projects from the fuel inlet side of chamber.

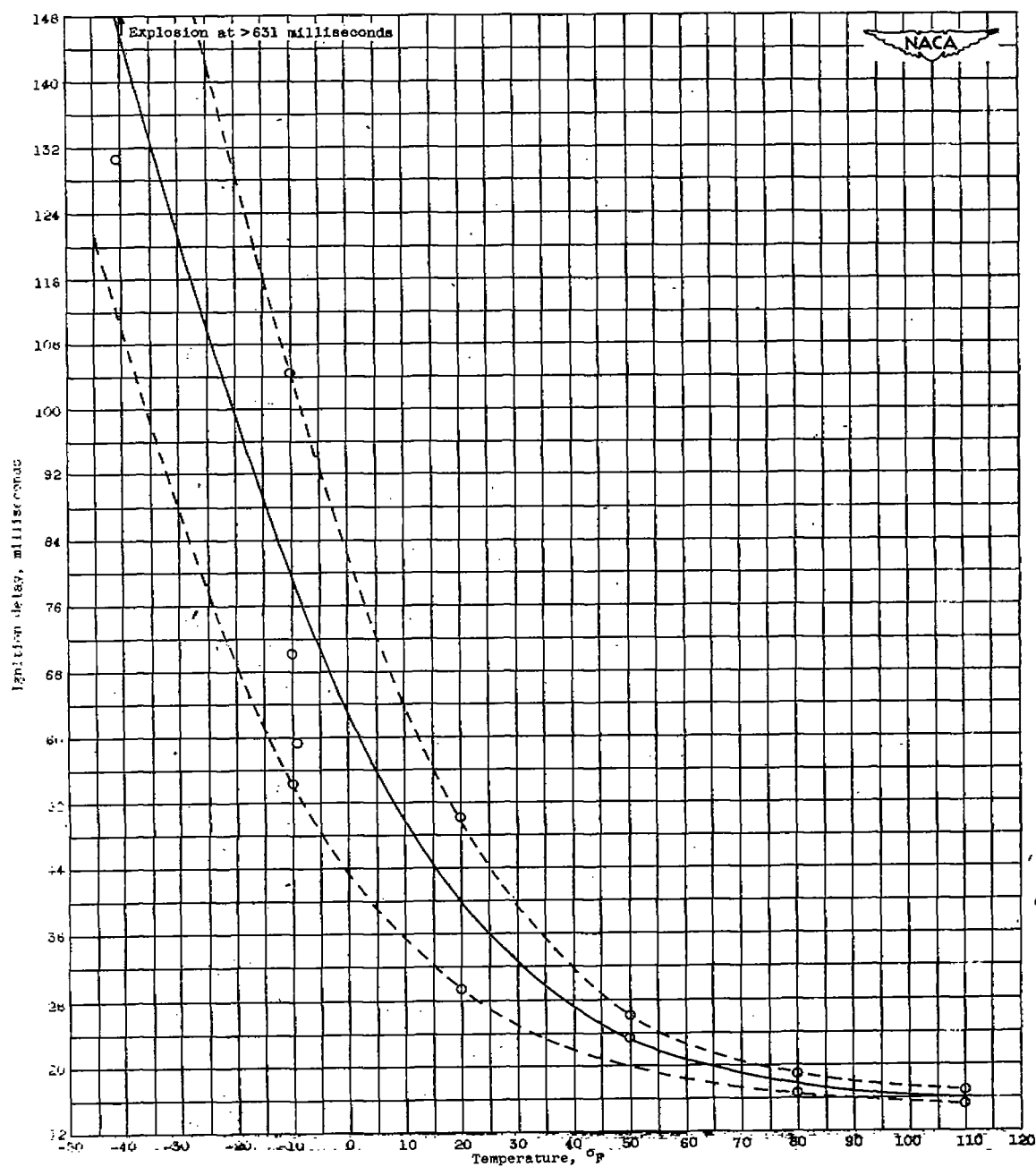


Figure 12. - Ignition delay of hydrazine hydrate and white fuming nitric acid (USAF Specification No. 14104) at sea-level pressure.

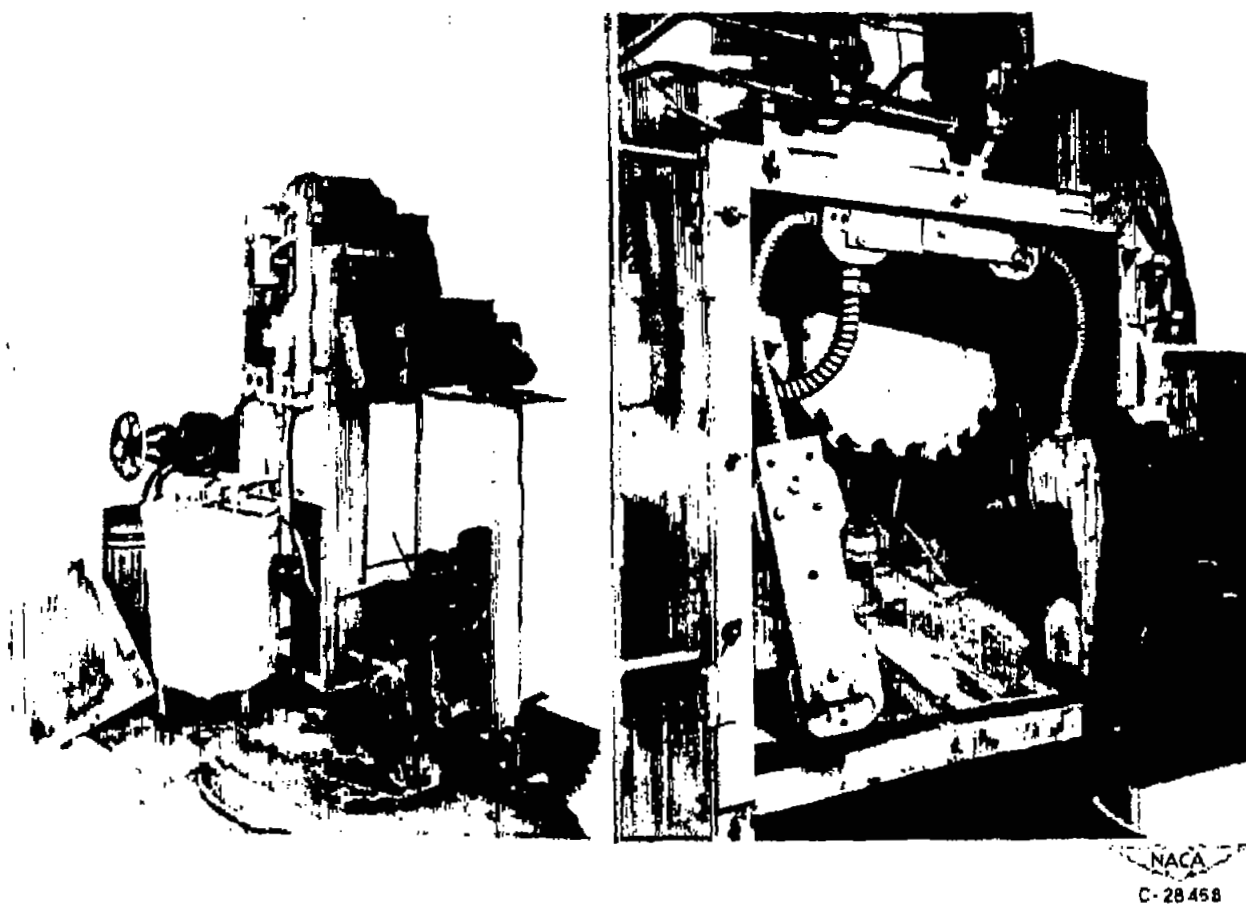


Figure 13. - General and detailed views of ignition delay apparatus after explosion of run 67.

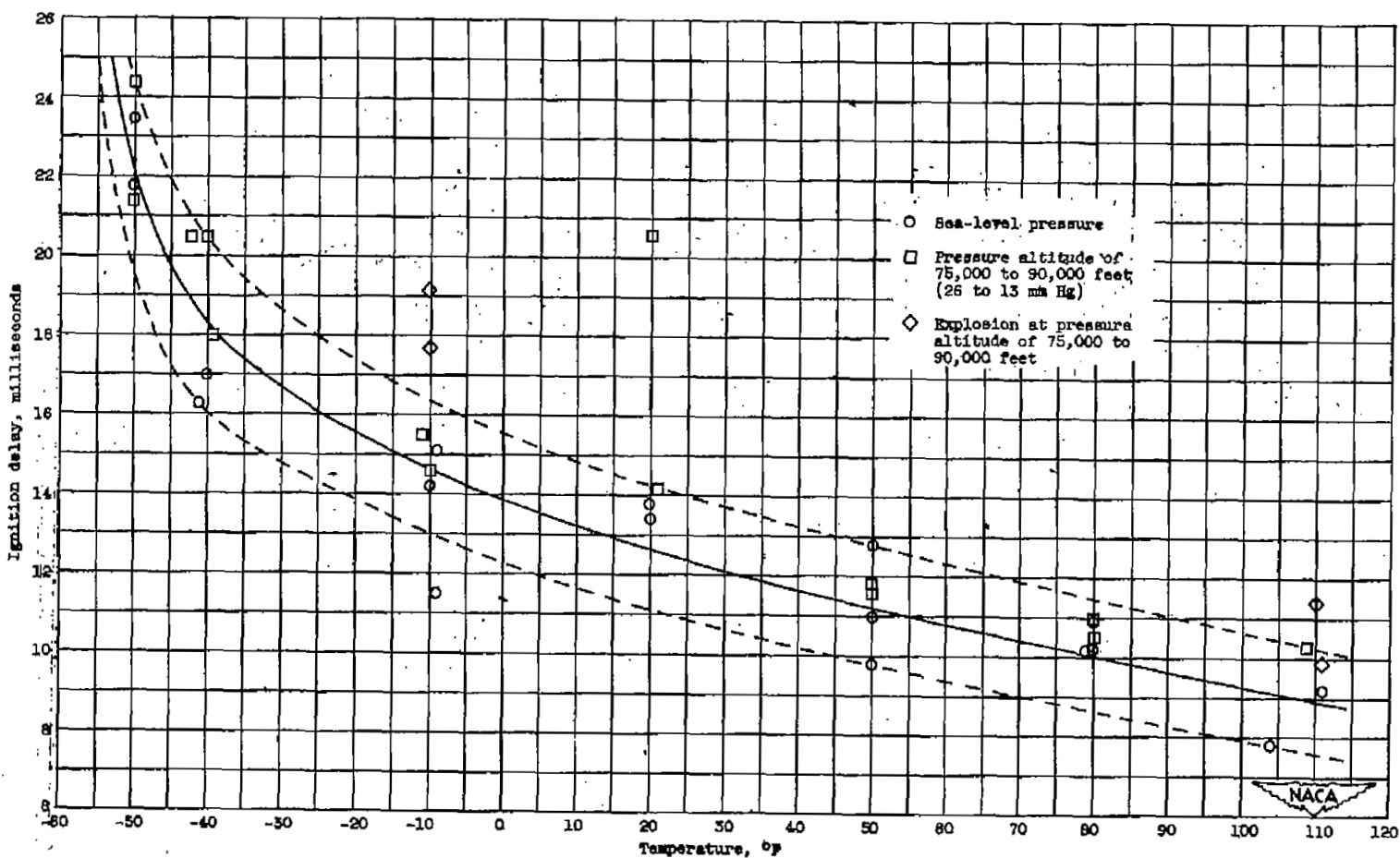


Figure 14. - Ignition delay of 57 percent diallylaniline and 43 percent triethylamine (by weight), and white fuming nitric acid (USAF Specification No. 14104).

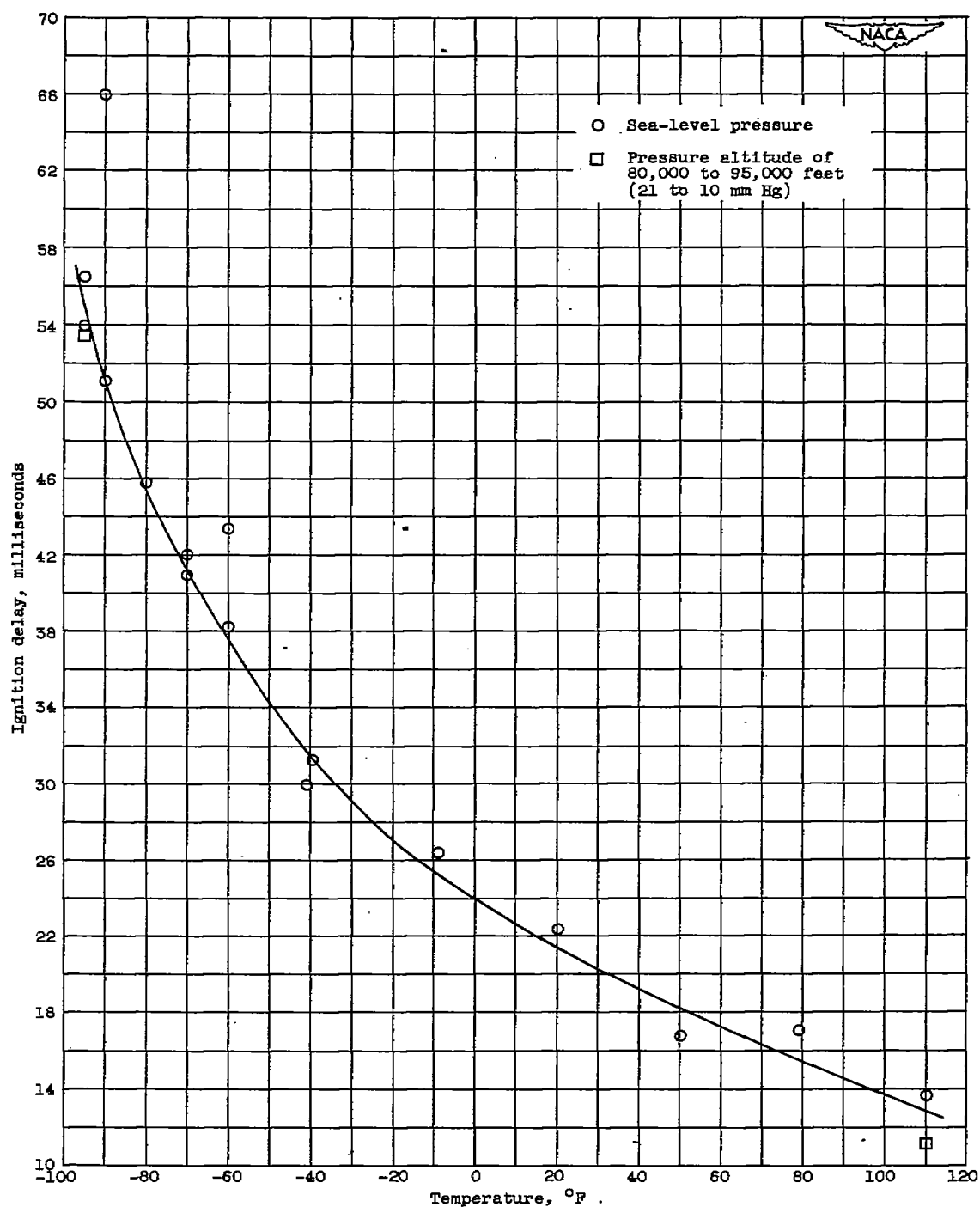


Figure 15. - Ignition delay of 57 percent diallylaniline and 43 percent triethylamine (by weight), and red fuming nitric acid containing 3.5 percent water and 16 percent nitrogen dioxide (by weight).

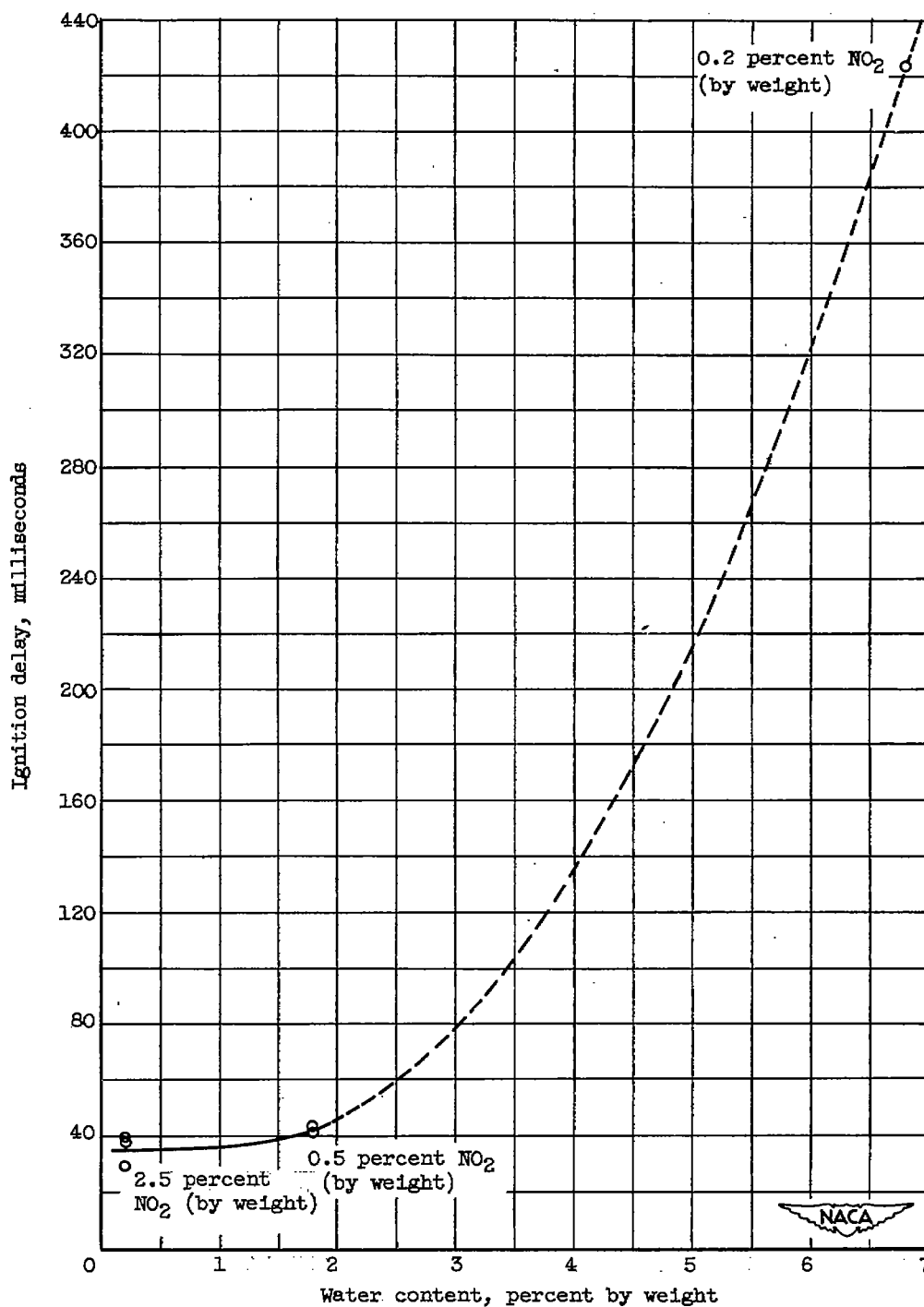


Figure 16. - Effects of water and NO₂ contents of nitric acid on ignition delay of fuel containing 50 percent triethylamine and 50 percent mixed xylidines (by volume) at -40° F and sea-level pressure.

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